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IMPROVED INSPECTION OF WOODEN VESSEL FASTENERS

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16. Abstract

The Coast Guard is responsible for the safety of over 2000 wooden vessels which carry passengers. In 1993, a vessel sank in the Chesapeake Bay with the loss of three lives. The investigation concluded that the sinking was caused by faulty fasteners adjacent to the keel. The National Transportation Safety Board recommended that the Coast Guard investigate methods to non-destructively evaluate fasteners. This report documents the evaluation of various nondestructive methods such as sounding methods, specialized drills, ultrasonics, stress wave techniques, a capacitor based system and x-rays. These techniques were tested under field conditions on a hull and in the laboratory.

Two x-ray techniques were the only methods which directly measured the condition of the fasteners themselves. Conventional x-rays were effective at identifying the fasteners and their condition. The real time x-ray system used in this study did not perform as well, but it shows potential due to its smaller size and faster processing speed. Other real time systems with stronger sources, currently on the market, are expected to perform as well as conventional x-rays. Neither technique can evaluate the condition of the wood immediately adjacent to the fasteners, although deteriorated wood is not usually found next to a good fastener unless the vessel has been refastened. The results of the x-rays should not be the only piece of information used to assess the condition of the fasteners. Information such as the vessel's history and visual clues should be combined for a total assessment.

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METRIC CONVERSION FACTORS

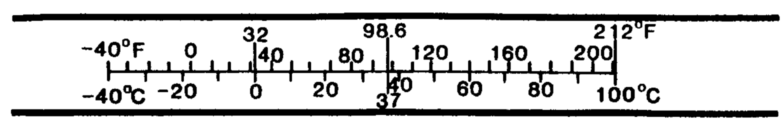
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (WEIGHT)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (EXACT)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly).

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (WEIGHT)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	0.125	cups	c
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (EXACT)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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EXECUTIVE SUMMARY

The Coast Guard is responsible for the safety of over 2000 wooden boats that are used as passenger vessels throughout the United States. The types of vessels include ferries, sight-seeing and charter fishing vessels, and any wooden boat that operates carrying more than six passengers for hire.

As a result of the sinking of the 32 year old wooden vessel EL TORO II in December 1993, with the loss of three lives, the National Transportation Safety Board (NTSB) recommended that the Coast Guard evaluate wooden vessel inspection techniques. The objective of this R&D Project was to review methods of nondestructive testing of wooden vessels and determine which ones may be applicable for use in Coast Guard inspections, and recommend methods that could be utilized by Coast Guard inspectors or vessel owners and operators to determine a vessel's condition.

Multiple methods of non-destructive testing (NDT) were evaluated. These included sounding, specialized drilling, ultrasonics, a stress wave technique, a capacitance based method and x-rays. The methods were both field and laboratory tested.

Only the two x-ray techniques studied directly evaluated the fasteners. Conventional x-rays were very effective at identifying the condition of fasteners. The real time x-ray did not perform as well. Neither technique could evaluate the condition of the wood immediately adjacent to the fastener.

It is recommended that the use of both conventional and real time x-ray techniques be considered for use in critical areas and unique situations when the inspector requires information about fastener conditions without dismantling the vessel, though these results should not be the only information used to make decisions concerning safety. The Navigation and Vessel Inspection Circular (NVIC) 7-95, Guidance on the Inspection, Repair, and Maintenance of Wooden Hulls, should include information on both conventional and real-time x-ray techniques.

1.0 BACKGROUND

The vessels under Coast Guard jurisdiction undergo a safety inspection in the water annually, and are required to be hauled out of the water at least every two years (five years for fresh water) for an underwater body inspection. In addition, any major modifications or repairs to a vessel must be reviewed, approved and inspected by the Coast Guard. Coast Guard marine inspectors receive initial training in wooden vessel construction and inspection techniques at the Coast Guard's Marine Safety School in Yorktown, VA, as part of a multi-week Marine Inspector Course. Those who are assigned to ports with a large number of wooden vessels may also be sent to a one week course specific to wooden boat construction, repair and inspection. Although training provides a good foundation, additional learning must be gathered while on the job. In most cases, a new inspector works closely with an experienced marine inspector or in some cases with a commercial marine surveyor. These individuals have much more knowledge about boat building and repair techniques, especially in their local areas.

The National Transportation Safety Board (NTSB) recommended the Coast Guard evaluate the effectiveness of its wooden vessel inspection program in response to the sinking of the 32 year old wooden vessel EL TORO II. The casualty investigation determined that the probable cause of the sinking was catastrophic flooding resulting from sprung planks in the hull below the waterline. Upon examination, the nail fasteners in three localized plank ends were found to be severely corroded. No visual clues were noted on the external surface of the wood to give an indication of corroded fasteners.

At the time of the investigation, the Coast Guard Navigation and Vessel Inspection Circular (NVIC) 1-63 "Inspection and Repair of Wooden Hulls," was the document that provided guidance to marine inspectors on wood boat inspection and repair. This circular did not specifically discuss the issue of removing fasteners to check their condition during an inspection. However, experienced inspectors had commonly been using this method of inspection, but without any regulatory or specific Coast Guard marine inspection program policy guidance to do so. The result was inconsistent application of this inspection technique throughout the country. The Coast Guard convened a Joint Industry/Coast Guard Wooden Boat Inspection Working Group to review NVIC 1-63. The result was the publication of a new NVIC, 7-95 "Guidance on Inspection, Repair and Maintenance of Wooden Hulls" in November 1995[1]. The Table of Contents of this circular is contained in Appendix A-1. This document provides guidance for removing fasteners "for cause" as well as consensus on periodic random sampling of "a minimum of eight fasteners per side below the waterline." (See Appendix A-2) The guidance provided recognizes the fact that any long-term maintenance program associated with wooden boats requires random periodic inspection of fasteners even if the hull is fair (even) and there are no visual indications of structural deterioration. NVIC 7-95 provides recommendations of specific areas for the samples to be taken. Specific recommendations for cross-plank vessels similar in construction to the EL TORO II are also supplied. This NVIC provides a more consistent approach for use throughout the Coast Guard.

In addition to the new NVIC, the Coast Guard also considered recommendations from the NTSB as a result of the EL TORO II casualty. Specifically, the Coast Guard considered Recommendation M-94-22, "Research and develop with the assistance of the wooden vessel industry, nondestructive inspection techniques for inspecting fasteners on wooden vessels." After some initial research on the availability and practical use of such technology, the Coast Guard initiated an R & D project through its Research and Development Center to identify some nondestructive inspection techniques for wooden hulls. The intent of the project is to find viable methods to determine the condition of wooden hull fasteners and the wood surrounding the fastener without removing the fastener and subjecting the planks and frames of the vessel to potential damage. Some initial work was performed by a cadet at the Coast Guard Academy as a First Class Project [2]. The R & D project consisted of the following steps:

1. Examine current wooden boat construction techniques.

2. Identify potential evaluation methods from the maritime and other industries.

3. Build a test fixture and/or obtain a wooden vessel as a test sample.

4. Evaluate the most likely techniques by using them on the test fixture and/or test hull.

5. Dissect the test samples and compare the actual conditions to those found with the non-destructive techniques.

6. Provide recommendations for future work and field use of the recommended techniques.

2.0 WOODEN BOAT CONSTRUCTION

There are many types of wooden boat construction techniques used throughout the United States. Construction techniques can vary from region to region, and are dependent on the type of wood available and the type and service of the vessel. The types of wooden vessels inspected by the Coast Guard range from late 19th century schooners, to plywood riverboats, to epoxy encapsulated strip-planked catamarans. For Coast Guard classification purposes, if wood supplies the structural integrity, then it is considered a wooden vessel even if it has a thin coat of material such as fiberglass on the outside. The techniques discussed here may not be applicable for all types of vessels, but should serve as a general description for this project. Since the major focus of this project is on the fasteners, the various types of wood used will not be discussed in detail. In standard wooden boat construction, the fasteners are usually hidden by a wooden plug (see Figure 1) or sometimes marine putty. Guidance from NVIC 7-95 on this issue is contained in Appendix A-3. Currently, the only way to ensure that a fastener is good is to remove and inspect it. For wood screws, this is typically not a problem. However, when removing nails or drifts from a wooden hull, significant damage to planks and frames can occur if the removal is not handled properly. This can result in the need to replace the damaged plank. In addition, the removal of fasteners also places an additional cost on the vessel owner. The problems associated with attempting to nondestructively evaluate a wooden boat are numerous. Throughout the

United States, there are a variety of woods, fasteners (see Figure 2), planking (see Figure 3) and structural arrangements. Many of these construction related issues are discussed in NVIC 7-95. Details may be found in books on boatbuilding. [3, 4] Additional references are listed at the end of the NVIC 7-95.

The most commonly used fastener material is hot-dipped galvanized steel. Other material that may be used include bronze and stainless steel. The latter two types can be found in multiple grades. All three types of fasteners have conditions where their use should be restricted. For example, stainless steel is susceptible to crevice corrosion, and should not be used in tight joints below the waterline. Unfortunately, many owners, operators and even some repair yards refasten with what is available or cheapest without regard to what was in the hull originally. This can accelerate fastener deterioration through galvanic corrosion.

There are many types and sizes of fasteners used in boat construction. The ones of primary concern are those fastening the planks to the frame and butt blocks. Because of the construction techniques and paint, these are sometimes difficult to find. In addition, sometimes the planks can be held in place by compressive forces when blocked during haul out. To mitigate this effect, Coast Guard inspectors have the authority to require a vessel to get underway during an inspection to look for excessive leakage or working of the hull in a seaway.

3.0 VESSEL INSPECTION

3.1 Standard Inspection

The tools that an inspector or marine surveyor uses for a wooden vessel evaluation are simple. The most frequently used tool is a hammer. The sound that the hammer makes indicates the condition of the wood; a hollow sound indicates wood that has deteriorated. The inspector combines this with a search for visual clues such as open seams, deformations in the hull form (unfair planks), or rust stains indicating fastener corrosion. Excessive wetness inside or outside the hull can also indicate a trouble area. Areas which have a history of problems in many vessels, such as the garboard, are very likely locations for closer evaluation and fastener removal. For a generally well-maintained vessel, the first problem in evaluating the fasteners is locating them because paint can easily cover the bungs. One of the quickest methods of locating fasteners is to tap with a hammer to locate frames or other internal structures. The higher pitch sounds indicate planks and frames in good condition, while lower pitch usually indicates decayed wood or loose fasteners. Some of the techniques evaluated in this project attempt to take advantage of this method. The hammer technique may not work effectively where a closely spaced transverse and longitudinal structure may keep the hull tight even if the fasteners may be loose or starting to deteriorate.

In NVIC 7-95, there are two general conditions which may warrant removal of fasteners (see Appendix A-4). First, fasteners should be removed when there are visual clues such as rust bleeding, when planks appear to have moved away from frames, or when there are indications of loose bungs, etc. This has been the typical approach taken in the past by inspectors and marine surveyors. Second, even a fair hull should have a random sampling of eight fasteners per side of

the vessel below the waterline removed periodically for examination. This should occur every five (5) years in salt water and every ten years in fresh water. Specific areas known as sources of problems, such as garboard seams and stem joints, should be closely examined and sampled. This recommendation should provide a consistent approach and increase the number of fasteners being pulled.

As discussed above, there are a large number of variations for wooden vessel construction. Inspection methods must be flexible enough to be useful in many situations. The techniques being evaluated should be able to:

1. Locate and identify fasteners.

2. Determine the condition of the fasteners and the surrounding wood.

Another requirement which surfaced during the test was to determine if any of the methods could provide clues as to the condition of the fasteners or the wood as the hammer technique does. It was hoped that something could be found to increase an inexperienced inspector's chance of locating a bad area. These locations can then be subjected to further investigation including fastener removal.

3.2 Nondestructive Inspection of Vessels

There have been nondestructive testing methods used to evaluate structures or components on vessels. The most well-known has been the efforts on the U.S.S. CONSTITUTION [5]. It was noted that the vessel seemed to be "drooping" at the bow and stern. A complete evaluation of the wood and fasteners was performed. The fasteners used in the CONSTITUTION are copper alloy drifts on the order of 3/4-inch in diameter and as long as five feet. An ultrasonic flaw detector was used with an "A" scan presentation. The signals can indicate if the pin is sound (Figure 4), or wasted (Figure 5). The same techniques have been used for fasteners on wooden Navy minesweepers [6].

The major structural wood components of the CONSTITUTION were measured by stress wave velocity measurements. This method has been used successfully on large structures to locate decay or to estimate the remaining strength of a member. More details of this method will be discussed in the next section. The data taken were backed up by microscopic investigations and chemical analysis

A general review of the use of nondestructive inspection methods for small vessels is given in Reference 7. This describes the use of a fiberscope in examining areas within a hull box section which was inaccessible. The use of thermography and ultrasonic flaw-detection equipment is also discussed. In the past, these advanced techniques were only used for unique situations when the only alternative was to take the vessel apart or cause damage in some other way such as taking a core sample.

When looking for information concerning the use of x-ray techniques on boats, a lot of anecdotal stories were uncovered. People had heard that portable x-ray equipment normally used for large animal veterinary medicine had been used to locate and evaluate keel bolts for sailboats. The added expense was preferred to cutting up a perfectly good vessel to check something that might not be a problem. The only reference to x-rays being used to evaluate plank fasteners on a vessel was by the Anvil Corporation of Bellingham, Washington. The vessel had never been inspected by the Coast Guard and was being converted from private use to a passenger carrying vessel. The local Coast Guard inspection office accepted x-rays in lieu of pulling many of the fasteners originally indicated as verification of the condition of the hull. Two examples are shown in Figure 6. For these shots, the basic arrangement is shown in Figure 7. The film is placed on the inside of the vessel and the source is located outside of the hull. The major problems faced are the accessibility inside of the hull and the angle at which the shot is taken. Not all of the fasteners may be accessible, especially some of those which are near the keel and considered to be crucial. For the documenting of this vessel with a length of 86 feet, 100 images were taken and the materials and labor were approximately $3500.00.

Another more sophisticated, system has been developed by Philips Industrial Automation and is based on x-rays that backscatter. The method, known as ComScan™, detects backscattered radiation and integrates the source and detector in a single unit, thus permitting single-sided inspection. By determining the time of the returns, the system creates a picture of the object in 3-D by taking slices at increasing depths(see Figure 8). A system is being developed by the Naval Research Lab (NRL) to evaluating rubber sonar domes on Navy ships in the water. This system is evaluated later in this report. Systems similar to this are also being developed for detecting land mines [8].

3.3 Nondestructive Evaluation of Wood Structures

Extensive research has been performed in the area of wood evaluation. Some of the most advanced methods of inspection have been adapted from other industries and fields for the wood industry. Several organizations, including the U.S. Department of Agriculture Forest Service, at the Forest Products Laboratory, have done extensive work for the lumber and utility industries [9]. Over the past 20 years the work has included sorting and grading structural products, evaluating utility poles and evaluating large structures. Most of the original testing involved laboratory-type tests with controlled samples to determine a wood's engineering characteristics. These data were used to calculate the remaining strength in wooden structural members based on the percentage of voids or decayed wood. This led to the approach that all of the voids and degraded areas do not have to be exactly mapped and that analysis can provide an overall assessment of the remaining life of the structure. Among the most useful techniques for evaluating in-place structures is stress wave velocity analysis. The time that it takes for sound to travel through an object is dependent upon the material properties and conditions. Decayed wood greatly reduces the speed at which the sound travels. Mechanisms which generate a pulse in the wood and measure the speed to get to a second sensor have been used on a football stadium, a school gymnasium, bridges, water-cooling towers and utility poles [9]. This method was also used to assess the condition and length of unknown timber piles [10].

Other techniques used in the past include static bending, transverse vibration, screw withdrawal and the Pilodyn test which measures how far a pin is driven into the wood. Of these methods, the first two are difficult to apply in the field because require large excitations or forces to deform the material. The problems with the last two tests are that only degradation near the surface is detected and only small areas are covered at one time.

There have been attempts to utilize computerized tomography, commonly known as CAT scans, to locate nails and voids in wooden utility poles. A portable unit was designed in 1986 [11], but was deemed to be too costly and it could not evaluate the portion of the pole below ground level. (see Figure 9) The Navy performed a feasibility study for an underwater CAT system in 1985 for use at docking facilities, but it was thought to be too large and costly. A group in Japan has also investigated the use of acoustic emissions in a laboratory setting to evaluate wood decay [12]. None of these methods appear useful for the inspection of boat hulls. The problem with most of these systems is one of access. It is not possible to get on all sides of the fasteners or structures in a boat due to additional structures, berths, water and fuel tanks, etc. A two-dimensional CAT system which converts the image to 3-D has been proven for bridge inspection [13] but is costly and time consuming.

Another technique to evaluate wooden structures is measuring drilling resistance. Using a special drilling device that penetrates the wood at a constant speed, the electrical current consumption is measured as a function of drilling resistance. This method easily detects spots damage by insects or fungi and can also be used to estimate the density of wood. [14]

4.0 EVALUATION OF METHODS

4.1 Test Pieces

A two-part approach was taken to obtain parts of vessels which could be used to evaluate potential technologies. A test fixture using standard boatbuilding techniques and known defects was constructed to serve as a control piece. The second was to find an existing vessel that could be dissected upon completion of the evaluation to determine the actual condition of the wood and fasteners.

4.1.1 Test Fixture

A wood hull test fixture was fabricated by McClave, Philbrick and Giblin of Stonington, Connecticut. The fixture was two feet by three feet and constructed of southern pine and white oak (see Figure 10). Galvanized bolts, screws, and nails were included as well as two plank butt ends. A portion of the planks were thinned from behind with a sander and a portion of one of the frames was dug out and a polyurethane foam adhesive/sawdust mixture put in place to simulate deterioration. The scantlings used are the approximate size for a 40-50 foot party fishing vessel that requires Coast Guard inspection. Additional details concerning the fixture, including the defect types, is given in Appendix B.

4.1.2 Test Hull

One of the main objectives of this project is to evaluate potentially useful technologies on an actual vessel. Boats still in active use could not be utilized as it would be dismantled at the conclusion of the tests. A source of vessels initially identified was a program sponsored by the state of Maryland which recovered and destroyed derelict vessels. By the time this project was initiated, the program had been discontinued. The few vessels considered through the program were pleasure craft (such as Chris Craft) that do not have the scantlings representative of a typical Coast Guard inspected passenger vessel. A derelict hull was eventually found in the town of Short Beach in East Haven, Connecticut. The vessel, the VOLSUNGA III, was a 39-foot Coast Guard inspected ferry vessel which was taken out of service and placed on blocks at the end of the summer season in 1994. (see Figure 11). The vessel was originally used to provide ferry service to islands in Long Island Sound. The vessel admeasured 10 gross tons and had a diesel engine for propulsion. It was built in 1969 with oak frames, cedar planking and clinched galvanized nails. Steam-bent sister frames and gussets were installed in 1986. Figure 12 is a sketch out of the Coast Guards inspection log of the vessel and a photograph of these frames is shown in Figure 13. Various sections had also been refastened with stainless steel wood screws

The first task was to document the condition of the hull. The hull was placed in the water for a couple of weeks to saturate the wood. The intent was to create a typical scenario that a Coast Guard marine inspector would encounter; that is, a vessel which is pulled out of the water for a few days for some work and is still wet. In this case, several commercial marine surveyors (see list in Appendix C) and Coast Guard inspectors evaluated the hull. This inspection was not typical in that the engine and most of the inside structure (ceilings, floors, etc.) had been removed thus providing a greater degree of access than normally encountered. This permitted a very thorough evaluation of the hull. The results of the three surveys submitted are described below.

The VOLSUNGA III had a carvel plank arrangement which was built over steam bent frames. This type of vessel is known as a "Novi" (as in Nova Scotia) style lobster boat hull. The original 1-inch by 3-inch frames were spaced approximately eight inches apart. Among the general comments was that these types of boats are considered "throwaway vessels," being used for 8-10 years and then discarded. In theory, the light structural members permit the vessel to flex in a seaway but maintain watertight integrity although the surveyors indicated that the structure is still deficient with respect to Coast Guard standards. Some of these types of vessels are sold to locations south of Maine at the end of their useful life and deserve added attention when encountered. The approach used for this vessel was much different than the robust designs normally utilized in offshore vessels. There are no stringers, deck carlins, nothing supporting the center of the transom, and some inferior grades of soft pine were utilized in a couple of areas. There were multiple problems listed in the surveyor's reports including a deflection of the hull at the stern of about 1 3/8 inches due to the blocking arrangement, numerous loose planks, butts that were located only on frames and many times too close together, and inadequate fastenings. Most of the bronze pieces for the rudder mechanism were found to be dezincified. Finally, the newer sister frames were never fully integrated into the floor timbers.

The surveyors were asked to identify typical types of trouble spots which they would like more information about if they had a nondestructive test method available. They were also asked to identify areas which appeared in fairly good condition to be used as control areas. The areas designed at test locations are shown in Figure 14 and described below:

Area	Description
1.	A five foot long area just below the rub rail. The condition of the area ranges from good to a hole which has been created due to rot. (Figure15)
2.	An area about two feet long extending about five feet along the keel. Seven questionable butts and a water intake are located in this section. (Figure 16)
3.	The port stern area includes checks, plank seams and a wire that can be utilized as a reference. The plank ends of the fore and aft hull planking are exposed. (Figure 17)
4.	This is the area near the keel located just forward of and including the stern post as well as a few planks up from the keel. (Figure 18)
5.	A generally good area above the water line but below the middle rub rail. Area is about 3 feet by 3 feet. (Figure 19)
6.	The entire stem area appears to have some problem areas. Some of the underwater section appears to be soft and the top of the stem head had large amounts of putty under the paint. (Figure 20)

There were a couple of other areas of interest such as the deflection of the stern. The surveyors indicated that the deformations were so large or visual clues so obvious that they would have required extensive dismantling of the hull if they encountered these types of problems in an actual vessel.

There are some problems with the inspection of wooden boat fasteners which this project did not address but were raised in discussions with the commercial surveyors. These include counterfeit fasteners that do not meet specifications and the use of bonded GRP joints where fasteners do not really supply support. All of these types of situations should be approached carefully and guidance should be obtained from NVIC 7-95, a knowledgeable marine surveyor or in consultation with the Quality Assurance Staff (G-MO-1) at Coast Guard Headquarters.

4.2 Technology Evaluation

A series of tests/demonstrations of the various techniques were performed during October 1996. Table 1 provides a complete list in chronological order. Some of these methods provide clues which may indicate areas of bad fasteners, some directly evaluate the fasteners while others evaluate the wood.

4.2.1 Sound Techniques

The first product demonstrated was SMART HAMMER (Patent Pending) which is a tool being developed by Bruce Pfund/Special Projects. The control component of this device includes some air actuators which can control the vibration of several impact devices. There are hand-held devices which either impact the surface at .5-1.5 Hz or vibrate at a higher frequency up to 25 Hz. In effect, this part of the device is a sophisticated hammer with a carefully controlled frequency and tapping force. The other major part of the SMART HAMMER is a microphone connected to a recorder by which data can be fed to a computer for processing. The computer analysis basically performs the function of an experienced surveyor's ear, tracking the frequency response to determine the good sections versus the questionable areas. For example, using the higher frequency vibrator device on Area 1 (see Figure 21), the results show a change in the sound signal shape when moving over areas ranging from good wood to rotten wood. The three-dimensional plots in Figure 22 shows the frequency on the x-axis (from left to right), the amplitudes on the z-axis (up and down) and time on the y-axis (in and out of the page). The individual lines are sets of data taken as the tool is moved along the hull. Note the range of frequencies involved and how the upper frequencies are not present for the rotten and loose areas. The difference in the good and loose areas can be more easily seen in Figure 23 where individual graphs at two specific times are shown. A sharp-tipped probe was also attached to the vibration piece and used on individual fasteners in an attempt to see if the response was the same for good and questionable fasteners. No differential sound was noted for any of the clinched fasteners. The contractor indicated that very loose fasteners were detected in a previous trial of the equipment.

The SMART HAMMER technique has a patent pending and is still in the developmental stage. The method appears to be capable of detecting wood density differences, loose planks and could decrease the time require to sound a hull. It has the capability of providing a permanent record and the approach appears to be standard enough to be consistently repeatable. A set of curves, such as those shown in Figure 23, may be useful in determining very good versus very bad areas, but additional information, such as visual clues, would still be required for a decision. It is not able to determine fastener condition and further development is needed to make it cost-effective and easily used in the field. Finally, the surface features of the wood greatly affects the results so that flaws beneath the surface may not be detected.

Another device on the market which utilizes the same principles is the Woodpecker by Mitsui. The system is designed for use in detecting delaminated skin on composite panels and "memorizes" a standard signal at a point which appears to be normal. The device is then passed over the other sections and light-emitting diodes indicate whether the new signal is different than the standard. There was not an opportunity to evaluate this system on wood, but the cost of a unit capable of saving the data collected is over $10,000. It appears to only measure the forces associated with the outer skin and could not detect imperfections deep in a solid structure such as wood. In addition, the lack of uniformity of wood which includes knots, would also preclude its use.

4.2.2 Specialized Drills

One of the techniques demonstrated was the use of specialized drills which can be used to detect decay and voids below the surface of the wood. These are normally used for large members such as bridge structures. There are systems on the market which drill holes smaller than 1 mm and can penetrate up to 16 inches into wood. The model demonstrated was the RESISTOGRAPH, manufactured in Germany (see Figure 24). The RESISTOGRAPH measures the drilling resistance by measuring the electrical current needed to penetrate the wood. The results are printed out on a paper inside the machine which displays the resistance along a 1:1 scale of depth in centimeters starting from the right hand side. Figure 25-a shows the lower resistance of the one-inch cedar plank, the higher resistance of the one-inch oak frame, and a small gap before the drill penetrates the plywood ceiling on the inside of the hull. Even though the hole drilled is very small, this technique would be considered a destructive test if used on the outer hull. If used on structure members on the inside of a vessel which are not responsible for watertight integrity, the hole would not be expected to cause sufficient damage to cause problems. Structural members such as the oak floors, shown with two measurements in Figure 25-b indicating a penetration depth of about seven inches, could be evaluated using this model.

The use of this method is most highly suited for larger, structural members. The variability of wood, due to knots, etc., could make it difficult for inspectors to detect the changes which would indicate questionable wood. Voids in members could easily be detected although the drills are highly area sensitive and the amount of drilling needed to cover a complete vessel is prohibitive. The cost of these units starts at about $4000. Their purchase may be prohibitive for all inspection offices except for those which regularly inspect large vessels such as schooners.

4.2.3 Stress Wave Techniques

One of the pieces of equipment demonstrated by the Forest Products Laboratory utilized stress wave velocity techniques which is one of the most widely used methods used for evaluating land based structures, such as bridges and stadiums. The technique has been proven to work over relatively large areas to detect rot. Voids, cracks and areas of lower density have also been detected. Other research has shown that wood loses much of its strength even before density changes can be detected. For this reason, detecting decay is very important for the lumber industry in assigning strength values which can be used for design and evaluating residual strength.

The measurement device demonstrated had a digital readout of the time in micro-seconds that it took for the sound to travel between the probes. These probes were hand held approximately one foot apart so that some of the variability is dependent upon the non-steady distance between the probes. The readings were consistent with the condition of the vessel as described by marine surveyors. The values measured ranged between 30 and 60 microseconds with the higher numbers recorded in suspect areas. The signal was lost at some discontinuities such as putty, but was not consistent. The signal was also lost at some seams and across one of the butts indicating a questionable area. It was thought that the sound may sometimes have found alternative paths

such as through the paint, or down, over and up through an adjacent plank. This appeared to be the case for the butt inspection.

Overall, this method appeared to point out degraded areas. But the level of resolution is far beyond that required by marine inspectors. The amount of loss in structural integrity detected by this method is not sufficient to cause problems in a planked wooden vessel. In addition, the paint and fasteners seem to cause problems in data interpretation just as knots would over relatively small areas.

4.2.4 Ultrasonics

Ultrasonics have been used for many years as a nondestructive tool for metals and composites. The major problem with wood is its lack of homogeneity which results in variable mechanical properties such as changes in density within the material. As a result, an ultrasonic gauge cannot be calibrated for sound speed. On the other hand, ultrasonics can be used on the metal fasteners.

The major use of ultrasonics in fasteners was demonstrated on the large pins (3/4 inch in diameter) of the USS CONSTITUTION. The unit used for the CONSTITUTION and this current evaluation was the Krautkramer-Branson Model USD 10 digital flaw detector. The sound created by the probe is transmitted into one end of the fastener. Since the standard ultrasonic probe for this unit is 1/4-inch in diameter, it is difficult to measure any fasteners that are smaller than 3/8-inch. Smaller probes are available. Only the rudder stock and rudderpost bolts were large enough to be tested and the test confirmed the visual inspection of dezincification. In addition, nails and wood screws do not provide a good backwall so a clean signal cannot be measured. This system is very useful for larger fasteners in the hands of a knowledgeable person. Only data collected by qualified companies and personnel should be accepted by an inspector.

4.2.5 Capaciflector

One of the more interesting techniques evaluated was the CAPACIFLECTOR developed for the National Aeronautics and Space Administration (NASA). This system is a capacitance-based, non-contact sensor technology that detects the presence and position of high dielectric materials. This is the same principle behind many of the moisture meters used for the inspection of fiberglass and composite boats, but the processing of the resultant changes in the electric field is much more sophisticated. Frequency of the input signal is selected and changes are detected in the amplitude and phase of the resulting field as influenced by the surrounding material. There have been many applications which have ranged from monitoring film thicknesses of less than 1/1000 of an inch to measuring fluid levels up to three inches away.

The probe selected for this demonstration was a developmental unit designed to permit the deep penetration of wood. It had a three-inch diameter footprint (see Figure 26). It was tested with kiln dried wood (moisture content much lower that that of the test hull) so that direct readings were not possible. Differential readings were taken by subtracting a baseline value taken in air, away from the hull, from a reading taken at the surface. As expected, the readings taken at a known

wet area, where water was dripping, provided four times the response than on most of the remaining parts of the hull. This indicated that most of the hull had dried out and the wood was no longer saturated.

Two areas were selected for measurements to be taken both above and below the waterline. Readings were taken in a 1.5 by 12 inch section of Area 6 (the bow) and a 12 by 12 inch patch in Area 3 (the port stern quarter). The readings generally were lower below the waterline than above.

Locations above the waterline were tested in Areas 1 and 5. In Area 1, dips in the readings were seen at two areas where the marine surveyors had indicated problems. (See Figure 27) In fact, it was marked right on the wood. But the dip at the 12 inch area is not consistent, especially since it is at a frame where the oak and fasteners should increase the readings. Area 5 was expected to be good and the data generally agreed except for a couple of areas on the left and top of the area (see Figure 28). Again, the data did not match the vessel frames as expected.

In Area 4, under the waterline, the readings were taken at a frame (see Figure 29). There was wood missing from around two of the bolts. In addition, the bolt was exposed at one location at ($y = 1.5$), missing from a second (at $y = 4.5$), and only a partial bolt was located at a third location (at $y = 7.5$). The readings are consistent here as a partial bolt and an empty bolt hole gave lower readings than the intact bolt.

The final area for this sensor evaluation compared two butt joints; a suspect butt joint below the waterline and what appears to be a good one above the waterline. The results show a dip in the readings at the questionable joint (Figure 30), but none at the good joint (Figure 31).

Overall, this technique did appear to detect changes in the wood structure of the hull although a rigorous analysis was not done to determine the actual conditions which were in place for both the wood density and moisture content. This technique currently requires processing back at the laboratory so development is still needed. It is still unclear if changes in fastener properties or even fastener locations are masked by changes in wood density or moisture content. Additional development work is needed to calibrate a system such as this and make it useful for field work.

4.2.6 X-Ray Evaluation

The remainder of the evaluation tests centered on the use of x-rays. Anecdotal evidence has surfaced in which sailboat owners have used x-rays to examine bolts which attached lead keels. The major documentation examined in this project was the result of the 86-foot vessel mentioned previously. The major problem is one of access. Normally, the source is kept outside the vessel and the film inserted between the inner vessel structure and the planks. This is not always possible so shots must be taken through multiple layers of structure. The key issue for this situation is then the interpretation of the results. Some knowledge of boatbuilding techniques is needed so that the different types of fasteners and wood utilized in the various layers can be determined. In the shots taken on the 86-foot wooden boat in the northwest, some wood grain

was also seen, but it is not clear how good wood is displayed in an x-ray as compared to rotten or water-saturated wood.

For x-rays there are multiple parameters such as angle of the shot, distance from the source to the film, type of film, etc. which could influence the results. In the evaluation that follows shots were set up to evaluate as many of these parameters as possible. The test fixture fabricated served as a known structure to verify the x-ray equipment's capability and be utilized for comparison.

The conventional x-ray equipment was supplied by Integrated Technologies, Inc. (iTi). The system used was an older model 1622 from Holger Andreasen (Denmark). It has a 200 Kilovolt (KV) capability with up to 4 milliamperes (mA) of current to drive the source. Figure 32 shows the source next to the test fixture. The images were processed in about 15-20 minutes in a portable darkroom contained on a truck specially configured for this.

The real time system was supplied by Ultra Image International, a division of Science Applications International Corporation, a well-known nondestructive testing company. This system is a Digital Radioscopy System (DRT™) and is shown in Figure 33 and its specifications in Figure 34. The source is a low level, pulsed unit to ensure safe operation. This particular system is not designed with sufficient energy to handle metals but is designed for special problems such as detecting plastic explosives in luggage, identifying damage in composite and aluminum aircraft structures, and inspection of printed circuit boards. As a result, the images are not as sharp as other portable, real time systems with a higher source level. This system currently sells for about $30K and a stronger source would be another $10-15K.

4.2.6.1 Test Fixture Evaluation

Shots were taken of the test fixture built for this experiment using both x-ray systems. The upper right-hand portion of the test fixture (see Figure 35) was targeted. The type of defects are described in Appendix A.

The conventional x-ray results (Figure 36) show the first problem encountered; the angle at which the shot is taken makes fasteners at different locations overlap and even appear not to be in the location thought. Note that the x-ray technician numbered the fastener from the side and the image is reversed because it is a negative. The shanks of the fasteners which were filed are easily seen.

In the real time shot (see Figure 37), a more limited area is covered. The results are a positive picture so that this shot is a mirror image of the conventional x-ray. Only fixture fasteners R5 and R4, and Butt 1 fasteners 6 through 10 are covered. The defects are easily seen.

Both systems detected the known defects within the test fixture. The resolution of the conventional x-rays was better than what is shown in this report due to the conversion from an 11-inch x 17-inch x-ray to an 8-inch by 10-inch picture. The wood grain lines are seen much clearer in the actual film. On the other hand, the real time results took only about five minutes

variety of software processing packages though the resulting images were still not as clear as the conventional ones.

4.2.6.2 Test Hull Evaluation

Based on the success of the shots on the test fixture, it was decided to examine the test hull. The six areas that had been designated for testing are shown in Figures 15-20. All of the areas that were designated had both conventional and real time x-rays. The areas where the location can be determined and the exact fasteners identified for both techniques are at the stern (Area 3) and at the bow (Area 6). These will be discussed in detail first before the other areas.

After the completion of the tests, the hull was cut up, the test areas saved and the remainder of the vessel was scrapped. The test sections were taken apart with help from Mr. Ed McClave, a wooden boat repairer and builder who also participated in the revision of NVIC 7-95. When dissecting the hull, the conventional x-ray images were relied on exclusively. The fasteners were extracted by splitting away the surrounding wood, disrupting the fastener as little as possible. The fasteners were identified with respect to the x-rays, numbered and given an evaluation as to the amount of corrosion. The wood surrounding the fastener was also examined carefully. Many of the clinch-nail fasteners in the lower section of the hull were so badly damaged that only the heads and the part of the shank in the planking remained. The results of the dissection is described along with the corresponding x-ray in the sections below. The areas from which fastenings were extracted were:

- The lower part of the stem, at, just above, and just below the painted waterline.
- The port quarter transom edge at the outer turn of the bilge, including the fastenings from several planks into the transom, again at, just below, and above the painted waterline.
- A section of the port side, including the garboard strake and two strakes above it, including the midship butt in the garboard strake, the associated frames, one floor timber, and a section of the keel.
- Two slices through the horn timber, stern deadwood and keel, which surrounded two vertical bolts in the structure. These bolts were mildly deteriorated.

Additional details concerning the dissection are given in Appendix D [17].

Stern

The stern area was unique because it was very accessible from the inside and outside. A view of the outside is shown in Figure 17 and the inside in Figure 38. There is no ceiling material that covers the frames at this location and the fuel tank did not extend to the corner. Note the nut in the oak timber to the left of the letter "A." This bolt is seen in both the conventional and real time

the oak timber to the left of the letter "A." This bolt is seen in both the conventional and real time x-rays (see fastener # 18 on the conventional x-ray in Figure 39). The outline of the oak timber can also be seen in the x-rays. The conventional x-ray was taken with two overlapping pieces of film attached to the outside of the hull and the source inside on the deck. (Figure 39) This shot was taken with the source approximately 36 inches away from the film. A 2½-minute exposure was used using 120 KV with 2½ milliamps. Examples of good fasteners are numbers 3, 4 and 5. These can be seen in the photograph in Figure 40. Note in the x-ray, the outlines of these fasteners are very distinct. The lighter color near the head is the wooden bung placed over the fasteners. Closer to the waterline, the fasteners in the x-ray begin to have less distinct shapes and almost seem to have a halo-type ring around them. In this case, the oxide created by the corrosion process has a different density. The effect can be seen in fasteners 7 and 9 in Figure 41 and fasteners 10 and 13 in Figure 42. On the other hand, for the stainless steel screws (11 and 12), the threads can be seen and found to be in excellent condition (Figure 42).

The real time x-rays of this area are not as clear although the screw which attaches the plastic clamp to the wire is plainly visible. A perpendicular shot (Figure 43) shows the bolt (#18 on the conventional x-ray). Note the outline of the washer seen alongside the bolt. A section of the long support bolt (located on the left-hand side of Figure 39) can also be seen. Figure 44 shows an angled shot taken at the same location. Even though the fasteners are not completely clear, the differences can be seen for the good fasteners in Figure 45 (fastener #5). This shot is darker because it was taken through the stern and the side (Figure 46).

Bow

The stem (Area 6) is typically a difficult area to inspect. Interior structures can limit access and some fasteners are completely inaccessible due to the construction techniques required for the knee area. The inspection can be concentrated on the exterior fasteners as long as the outer planks keep moisture away from the interior sections. The conventional x-ray of the stem utilized a 17-inch by 13-inch film (see Figure 47). The clarity of the x-ray was reduced when converted for this report so that not all of the 42 fasteners identified by the x-ray technician can be seen here. The stem has a one-inch-wide bronze band, seen down the center of the x-ray, with two pieces butting together just below fastener #27. Close-ups are seen in Figures 48 and 49. The x-ray was taken with the source inside of the hull (see Figure 50). Note the inside structure and ceilings with fasteners in various directions. As was the case for the stern, the fasteners above the waterline (above the butt joint in the bronze stem band) appear to generally be in good condition. There are a few ceiling nails pointing from the center out on both sides of the x-ray.

Just below the center of the x-ray in Figure 47, the washer (near the center of the figure) and the head of a bolt (nearer the bottom) can be seen. This was a major attachment of the stem to the knee and is in generally good condition although the x-ray does not provide any information. Near the bolt there are several partially corroded fasteners just to the right of the stem band. The center of the fastener which still has good metal is surrounded by a slightly lighter layer of oxide. The difference can be seen in the actual amount remaining in the fasteners in Figure 51. The upper fasteners (15,22,23,32) are all in good condition while the ones located below the waterline show extensive wastage as predicted by the x-ray. It is important to note that all

these type of references can help provide a relative wastage rate. The x-rays did not detect large splits in the wood caused by the larger nails.

The real time x-rays were also taken with the source inside of the vessel. The three shots shown in Figures 52-54 start about 40 inches down from the deck level and step down about 8 inches each time. The butt joint in the stem band can be seen just above the center in Figure 54. There are two issues involved in viewing the figures here. First, the source was moved to different locations between some of the shots so that the relative position of the fasteners changes. Second, the lower energy real time system had some difficulty penetrating the large amount of structure as can be seen in Figure 54. These two issues, plus the lack of reference points, such as the bronze bolt, make it difficult to interpret the results.

Other Areas

There were x-rays taken of other parts of the vessel, but conventional and real time shots were not taken in the same place. Real time shots were taken of Area 5 because the equipment was portable enough to be moved to that area. (Figure 55) The plank and the ceiling fasteners can both be seen. As expected, the fasteners in this area are in good shape and this was confirmed when taken apart (See Figure 56) Holes can be seen where the fasteners were removed.

Some real time shots were taken through the keel just forward of the propeller. Figure 57 shows a hull-mounted zinc anode, two screw fasteners and several nails. Figure 58 shows two keel bolts, one in front of the other. Figure 59 shows one of the bolts after dissection. Although these shots provide some information, the real time system did not have sufficient energy to penetrate the five inches of wood and provide sufficient resolution.

The final set of two shots were conventional ones of the keel adjacent to the engine cooling water intake. This can be seen back in Figure 16 and the x-rays are shown in Figures 60 and 61 with up to six minutes of exposure. Debris in the bilge, such as hooks and a staple, can be seen. It is difficult to positively identify all of the fasteners in this area and most of them completely disintegrated when this section was taken apart. It is also difficult to determine which side of the vessel the fasteners are on. Those that did not disintegrate remained embedded in the plank and frame and snapped when these were separated. Fastener 11 in Figure 60 (also seen as #15 in Figure 61) is shown in Figure 62.

The x-ray technicians generally read the conditions of the fasteners correctly with few discrepancies when reviewing the conventional x-rays. It appears that the condition of very good and very bad fasteners can be determined. However, the in-between region is a little questionable and the real time x-rays are not as conclusive. As a result, it was decided that a set of x-rays was going to be taken in a more controlled setting. Sections of the boat which were not previously dissected were set up in a laboratory at the R&D Center.

4.2.6.3 Laboratory Shots

The first set of x-rays were taken of a six-inch square section of the keel which contains two through-bolts (see Figure 63). Note the nuts partially visible on the right and a stainless steel screw on the side nearest the camera. There is an identical screw on the opposite side. These bolts were located about 18 inches from one shown in Figure 60. It was expected that the condition of the bolts would be about the same. For the conventional x-rays, the exposure time was 4-6 minutes at 140 KV and 3 milliamps. The necking of the fasteners can be seen in the conventional (Figure 64) and the real time shots (Figure 65) taken at zero degrees. The effect can be seen in the other four shots as well (Figures 66-69) taken at 30 and 45 degree angles. These shots also show how fasteners can hide behind other ones so that orientation of the source is important. Finally, the size of the bolts on the x-ray varies with the distance that the film is from the fastener. Thus, rod "B," which is closer to the film, has truer dimensions which can be measured right off of the film, especially for the 30 degree film. Larger separation distances change the angles and therefore increase distortion.

A series of shots was also taken on the section of the hull dissected from Area 2. The objective of this group of shots is to provide some standard types of arrangements which will help film interpretation. It is also important to note that these shots were not taken through the entire keel as those originally in Area 2 and resulted in a clearer picture. The first conventional shot (Figure 70) is taken from about 20 degrees below the planks. The point of reference used for this and the remaining figures is the sheetrock screw up about a quarter of the picture from the bottom. The better condition of the fasteners in the upper portion of the picture is obvious. The next shots were taken at a 30-degree angle from the side (Figures 71 and 72) and cover parts of two frames. Both techniques indicate questionable fasteners, but the conventional x-rays make it very easy to identify the loss of material of the shanks.

For the shots taken at a 45 degree angle, two different films with different speeds were used. The normal medium speed (ASA 80) is used in Figure 73. For these shots, the film was placed back to back and only one exposure time was necessary. As a result, the faster film (ASA 100) shown in Figure 74 appears darker. In actual use, the exposure time could be reduced for this faster film or a thicker piece of wood could be examined. Both show the condition of the fasteners in sufficient detail, although the light film picked up other details. The real time shot (Figure 75) also detects the fasteners. In addition, the 45 degree shots show that fasteners are in two pieces which is not as obvious in the real time 30 degree shots, especially for the fastener just above and to the right of the sheetrock screw. Also note that the fasteners near the bottom of all of the figures have lost the clinched ends. These detached when the hull was disassembled and they contained insufficient strength. A real time shot was taken at a 60-degree angle (see Figure 76). Although the condition of the fasteners can be determined, the distortion is very severe and this amount of angle should only be used for special cases.

Finally, two shots were taken of a bent frame from another vessel to show the difficulty in interpreting results due to coatings. Figure 77 shows a view of the frame and a corresponding x-ray in Figure 78 (shown on top of a 2x4). Even more dramatic are the coatings shown in Figure 79 which result in an x-ray with varying density (see Figure 80). The changes in the darkness of

79 which result in an x-ray with varying density (see Figure 80). The changes in the darkness of the x-ray are due to wood density, coatings and thickness of the piece, so all these variables have to be considered when using x-rays.

4.2.6.4 Backscatter X-ray

An x-ray backscatter method was attempted using a system developed by the Naval Research Laboratory. A set of images is seen in Figure 81. Each image represents a 50 mm by 100 mm (about 2 inches by 5 inches) slice about 0.5 mm thick. It is easy to identify caulk, screw hole filler, fasteners and changes in wood density. The hole filler material is seen up to about level 11 or 12 where the heads of the screws appear. The shadow of the heads continues on the images as deeper shots are taken.

An extensive evaluation of the system was not performed due to time constraints and the fact that this system is the only one known to be developed for maritime use. It appears to have the same problem of the other x-ray systems; when shooting perpendicular to the surface, the head of the fastener masks the body. The head also blocks the view of the wood surrounding the shank. Extensive developmental work would be needed to adapt this to take pictures at sharper angles.

4.2.6.5 X-ray Cost Comparisons

The x-ray firms utilized in this study require a minimum charge for 4 hours of work of about $400-500 for either the conventional or real time methods. This is expected as an average throughout the industry. Four hours should be more than sufficient for the conventional method to examine the "eight fastenings per side below the waterline" as recommended in NVIC 7-95. (See Appendix A-4). The real time technique could be completed in less time.

Comparing the conventional and real time x-ray costs to the current methods results in a wide range of time and costs. Screw type fasteners are relatively easy to remove and examine. The coatings and wooden plug are removed and the screw is backed out. There are several options at this point which is generally left up to the inspector:

1) If the fastener and wood both appear in excellent condition, the screw is reinserted.

2) If the fastener is generally good but some minor wood deterioration is found, the next larger size screw is inserted.

3) If moderate wood deterioration is found but most of the adjacent wood is good, fasteners can be inserted in the good areas and the old hole plugged up

4) If the wood and fastener are deteriorated, then a plank and/or frame may have to be replaced.

The action taken by an inspector depends upon the severity and location of the problem area. The first three options are generally low- cost (maybe $50-100 per fastener) and minimal time (1-2 hours per fastener). If complications arise such as breaking a fastener or stripping the screw head the costs and time can go much higher. A plank removal and replacement can take several days and cost over $1000 depending upon the location of the plank being removed, the vessel size and method of construction. One surveyor in Maine routinely pulls one-half inch diameter fasteners out of schooners by welding a rod to the end. Several other marine surveyors have mentioned performing this type of pull as well. Minimal damage is caused so the plank usually does not have to be replaced.

In general, nail removal may be more difficult depending on the size and type of nail used. In some cases there is a greater chance that the plank may be damaged locally and some rework required, as sufficient wood must be removed to get a cats paw or equivalent tool to reach the nail head. The effort required becomes equivalent to the final option for removing screws as described above. Thus it can vary and may involve several days work and cost over $1000.

5.0 CONCLUSIONS

5.1 Nondestructive Methods

Of all the methods investigated, only the two x-ray techniques directly measured the condition of the fasteners themselves. Conventional x-rays were effective at identifying the fasteners and their condition. The real time x-ray system used in this study did not perform as well but it shows potential due to its smaller size and increased processing speed. Other real time systems with stronger sources that are currently on the market are expected to perform as well as the conventional x-rays. Neither technique can evaluate the condition of the wood immediately adjacent to the fasteners, although deteriorated wood is not usually found next to a good fastener unless the vessel has been refastened. The orientation of the wood grain can be seen in the x-rays. This may be useful information in some cases where paint does not allow the determination of the type of planking used. The results of the x-rays should not be the only piece of information used to assess the condition of the fasteners. Other information such as the vessel's history and visual clues should be combined for a total assessment.

The cost of performing x-ray inspection is comparable to major fastener pulling efforts and repair. It is cost prohibitive to x-ray an entire vessel, but evaluating areas of interest is cost effective, as a single x-ray is capable of evaluating multiple fasteners.

Several of the techniques demonstrated during this project may be useful for locating question-able areas. Additional development is required for SMART HAMMER and CAPACIFLECTOR to be used in the initial phases of an inspection. Extensive testing is needed to develop repeat-able, calibrated methods which are capable of handling all of the variables such as material properties (wood, fasteners, coatings, caulking materials, etc.) and various wooden vessel fabrication and repair techniques.

Specialized drills and ultrasonics can be useful during all phases of inspection for unique situations, mostly for larger vessels with large structural members and fasteners. The stress-wave technique may also be useful for larger vessels as well but would need extensive calibration and development of test procedures. The multiple paths and discontinuities in vessel structures may cause complications for this technique and may preclude its use.

5.2 Inspection Process

Conclusions concerning the inspection process are of two types; general inspection issues applicable for any vessel and issues unique to vessels like the VOLSUNGA III. Many of the general inspection concerns have to do with accessibility. Faults noted by the inspectors may not have been found if the vessel was inspected afloat and the deck boards, engine cover or other structure were in place. The garboard area adjacent to the keel on the VOLSUNGA III is an excellent example of this type of problem. Serious consideration should be given to opening up interiors of vessels to reveal additional structure to alleviate this kind of problem. The process may be time consuming but does not need to be destructive.

Defects may also be hidden if the vessel to be inspected has been cleaned up, a fresh coat of paint applied and/or has been saturated with water. Due to the type of construction and the method of blocking the VOLSUNGA III on land, there were sections in which planks were firmly pressed together. The pressure held the planks firmly in place even though, as the x-rays indicated, the fasteners were not holding. The result was a generally tight vessel, although one could argue that there was enough other evidence, such as the distortion of the stern, to support a contrary opinion. An owner could argue that this distortion was only caused by the blocking and an inspector would have to make a case of showing how the vessel's structural integrity is still questionable.

The marine surveyors emphasized that inspectors should carefully review any structural modifications. Modifications may appear significant, but may not adequately address the real problems. For example, the sister frames installed in the VOLSUNGA III were designed to compensate for the deterioration of the adjacent frames, although the addition of a large amount of new wood did not adequately enhance the structural strength since the original design was generally weak.

An argument used by some owners that hull integrity be based on past performance should be received with skepticism. The EL TORO II was performing satisfactorily right up to losing a plank. The VOLSUNGA III could have performed satisfactorily in limited service in spite of the structural weakening of fasteners identified by the x-rays in this evaluation. The recommendation contained in NVIC 7-95 that inspectors ride the vessel underway should be reinforced, as this may be the only way to detect questionable areas.

The overall fastening scheme is just as important as the individual fasteners. The type, location, and use of fasteners should be considered. The multiple types of fasteners identified by the x-rays may not have been apparent to an inspector. An understanding of the corrosion process is also required. Just because the head or clinch of a nail appears to be in good condition, does not

necessarily mean that the shank is okay. This was seen in the x-rays of the keel. A more advanced discussion of corrosion is contained in Appendix C and NVIC 7-95.

Light vessels similar in construction to the Volsunga III are subject to deterioration more severe than normal wear and tear would suggest. Soft cedar planks in combination with clinched nails, provide a mechanism for nails to pull right through the planks if the heads deteriorate excessively. In addition, shallow bilges reduce air circulation that can result in major fungal problems, especially when combined with heat from the exhaust. The decks of such lightly constructed vessels should be picked up, especially if there are any signs of leaks or decay in the floor or overlay. The dissection of the Volsunga provided clear indication of this deterioration. In addition, these vessels are usually privately owned thus Coast Guard inspectors are not familiar with them. Local marine surveyors are a good source of information for unfamiliar vessels and should be consulted as needed.

6.0 RECOMMENDATIONS

It is recommended that the use of both conventional and real time x-ray techniques be considered as a nondestructive inspection technique for unique situations such as critical areas and special or antique vessels if the owner does not wish to remove and examine fasteners. For the evaluation of plank fasteners, the angle of the shots should not exceed 45 degrees. For keel and larger bolts, a perpendicular shot should be pursued. For all cases, the film should be as close to the fasteners as possible. The inspector should work closely with the x-ray technician in setting up the shot and the interpretation of results. The results of the x-ray should not be the only information used to evaluate the condition of a vessel. All aspects of the vessel's condition and history should be taken into consideration.

As the use of x-ray increases, the techniques will be improved and knowledge of them will grow throughout the industry. Some approaches which might enhance the x-ray techniques evaluated here are:

a) Improve access to more structure by using other sizes of film as small as 4" by 10" and flexible film cassettes

b) Improve structural coverage by using newer and smaller x-ray sources which can penetrate more material and be placed in more advantageous locations

c) Enhance wood grain detail through calibrated energy level adjustment

d) Improve x-ray location precision by:

    (1) having the inspector/surveyor number the frames and planks so that the X-ray technician knows the locations

(2) recording the exact location of the source and film including all angles and the distances the film and source are from the target fasteners.

(3) carefully numbering the images and noting their positions on the x-ray itself

(4) developing a metal target which could be attached to the vessel with it's location carefully measured to serve as a reference point for unique situations. This may assist when shooting through several layers of structure.

e) Improve real time x-ray definition by using stronger sources

Future efforts might include adding an appendix to NVIC 7-95 covering non-destructive testing. This report could serve as background and other experts could contribute. Future research should focus on advancing the methods currently used to identify problem areas. An experienced inspector can utilize visual clues and the hammer technique to identify questionable areas but an inexperienced inspector does not always possess sufficient knowledge. Further development of methods such as SMART HAMMER and CAPCIFLECTOR have the potential of providing quantifiable results. The information supplied could supplement the training and knowledge of an inspector if cost effective and easily used techniques could be developed.

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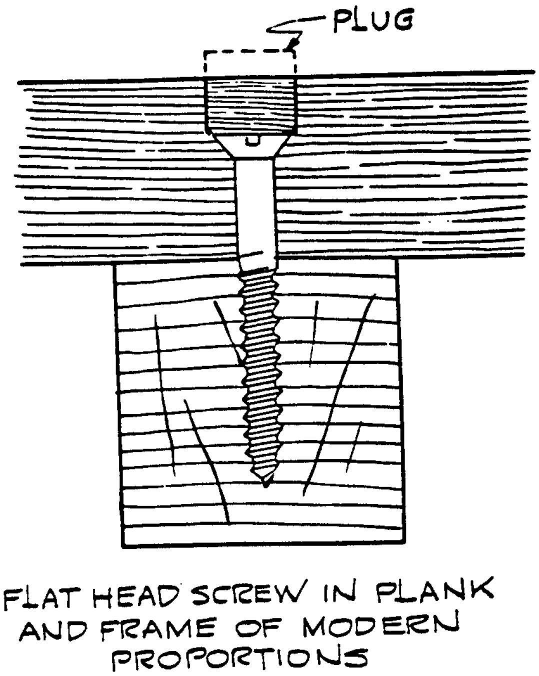


FIGURE 1. Typical Wood Screw Arrangement [1]

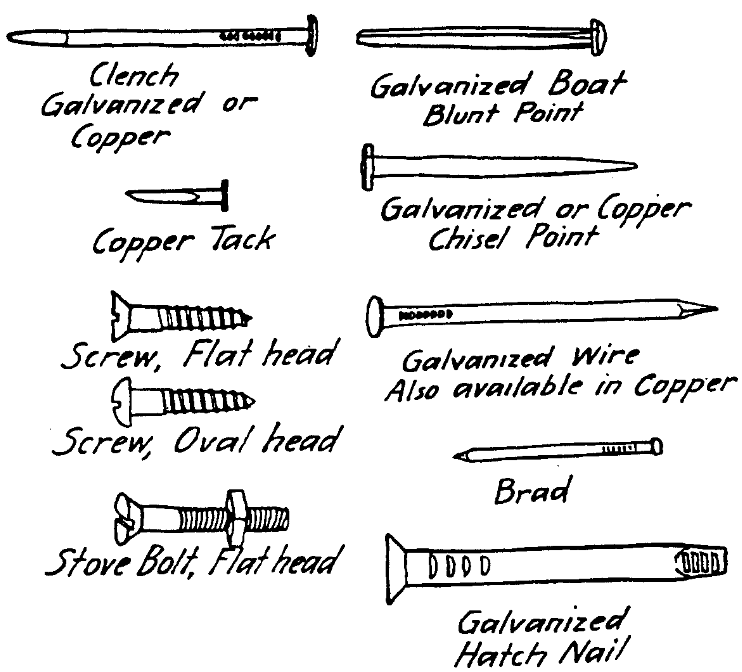


FIGURE 2. Common Plank Fasteners [3]

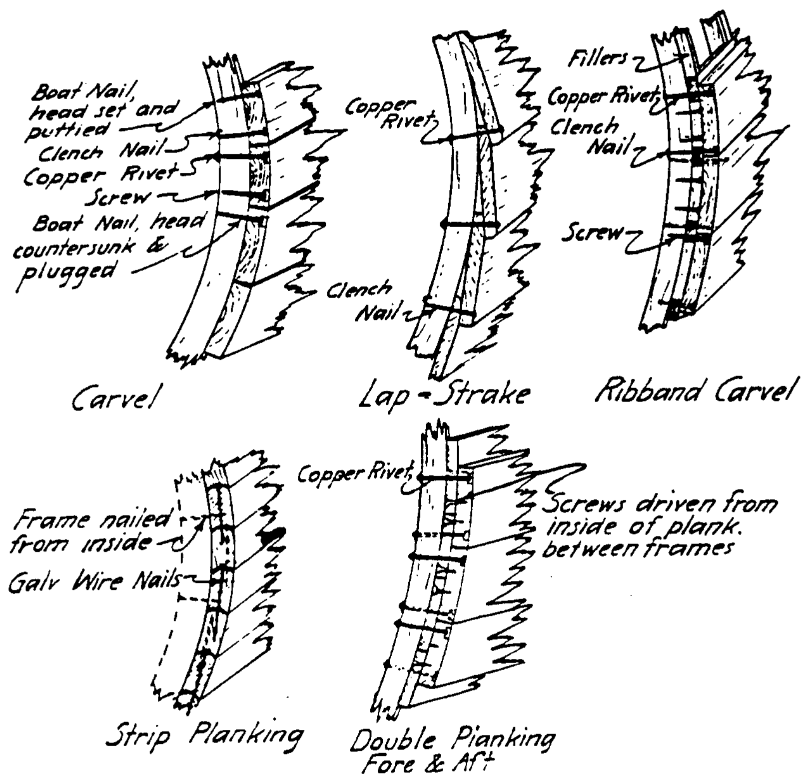
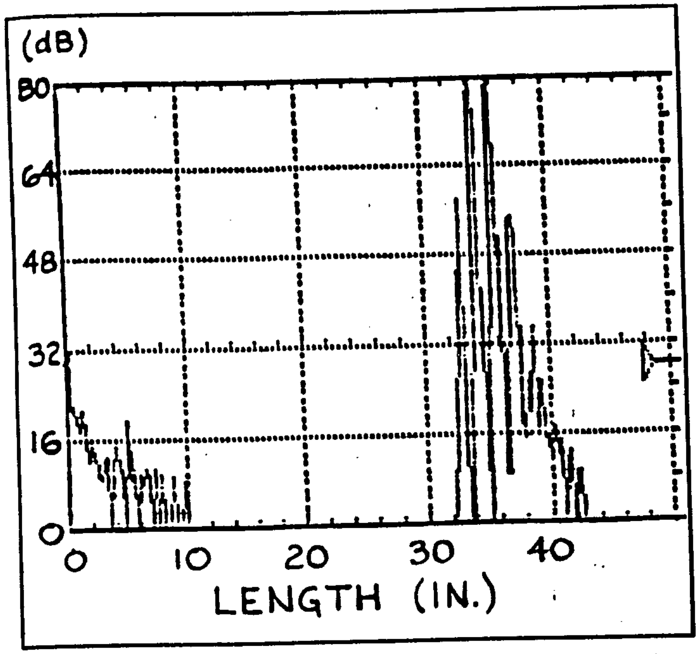
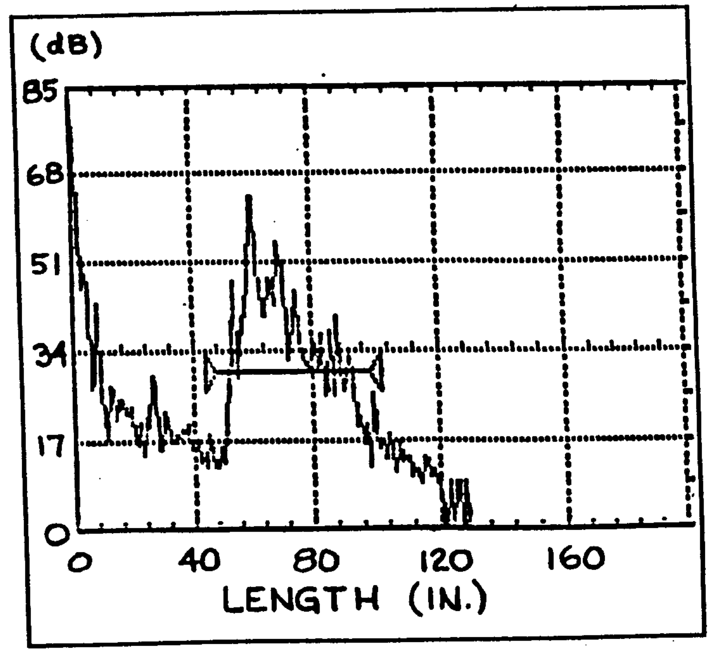


FIGURE 3. Common Types of Planking and Methods of Fastening[3]



A-scan of 32-inch long copper alloy drift pin in the starboard sister keelson (sail locker area). The pin is in good condition with light wastage on the inboard 8-10 inches.

FIGURE 4. Ultrasonic Output Showing a Good Fastener



A-scan of lower breasthook centerline fastener in the oil locker. The absence of a backwall indicates that this fastener is defective.

FIGURE 5. Ultrasonic Output Showing a Bad Fastener

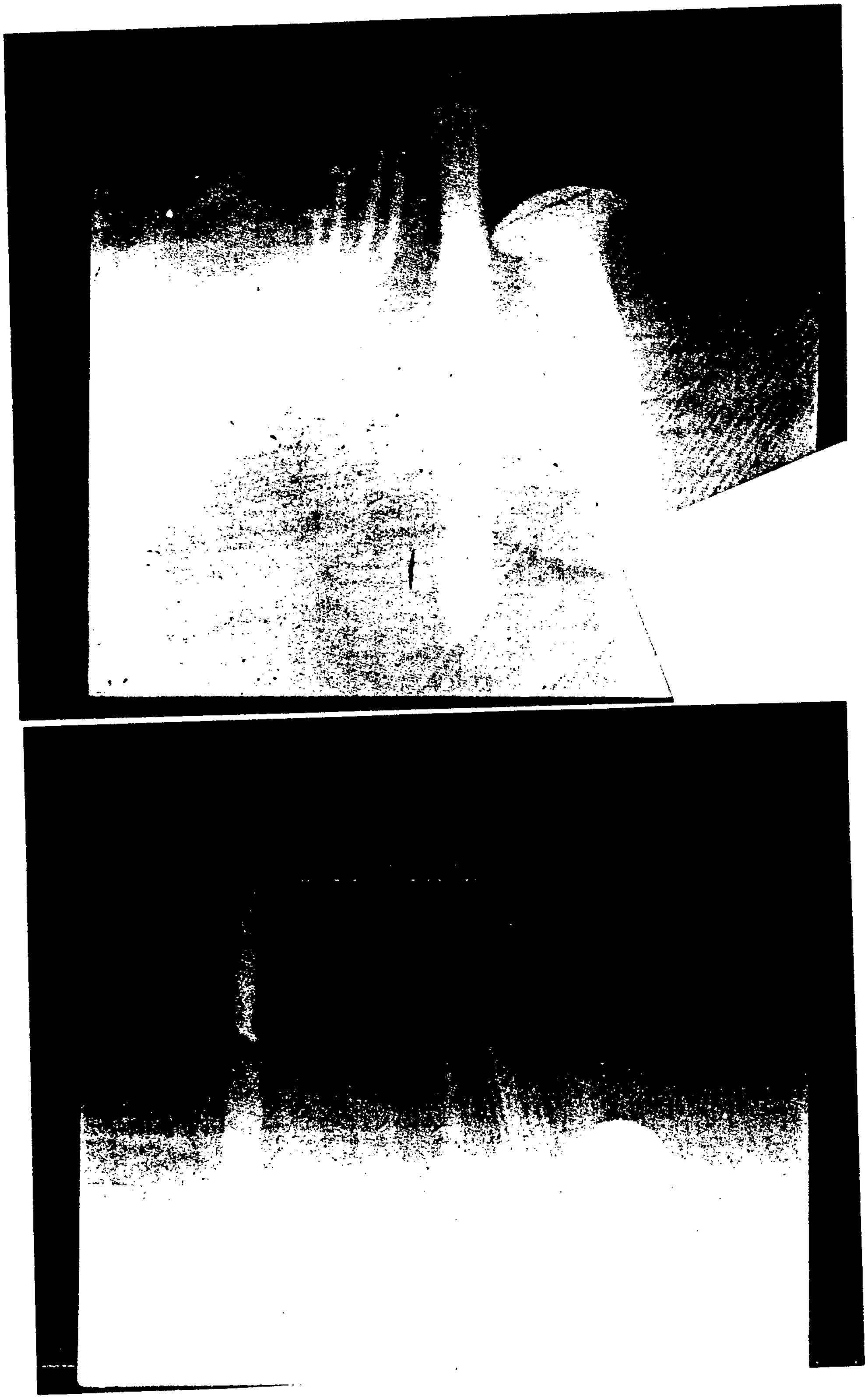


FIGURE 6. X-rays of Plank Fasteners

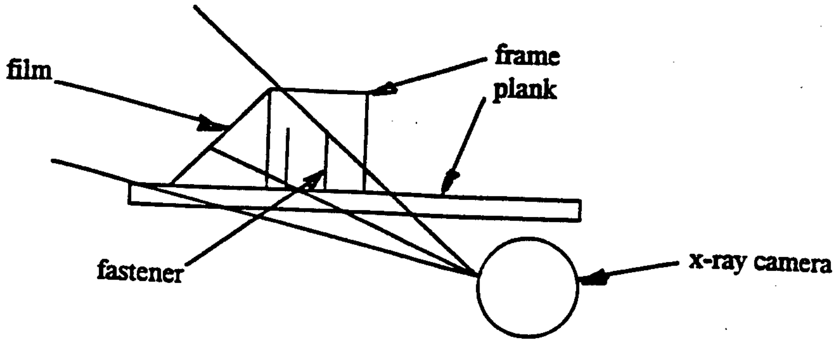


FIGURE 7. General Arrangement for Plank X-rays

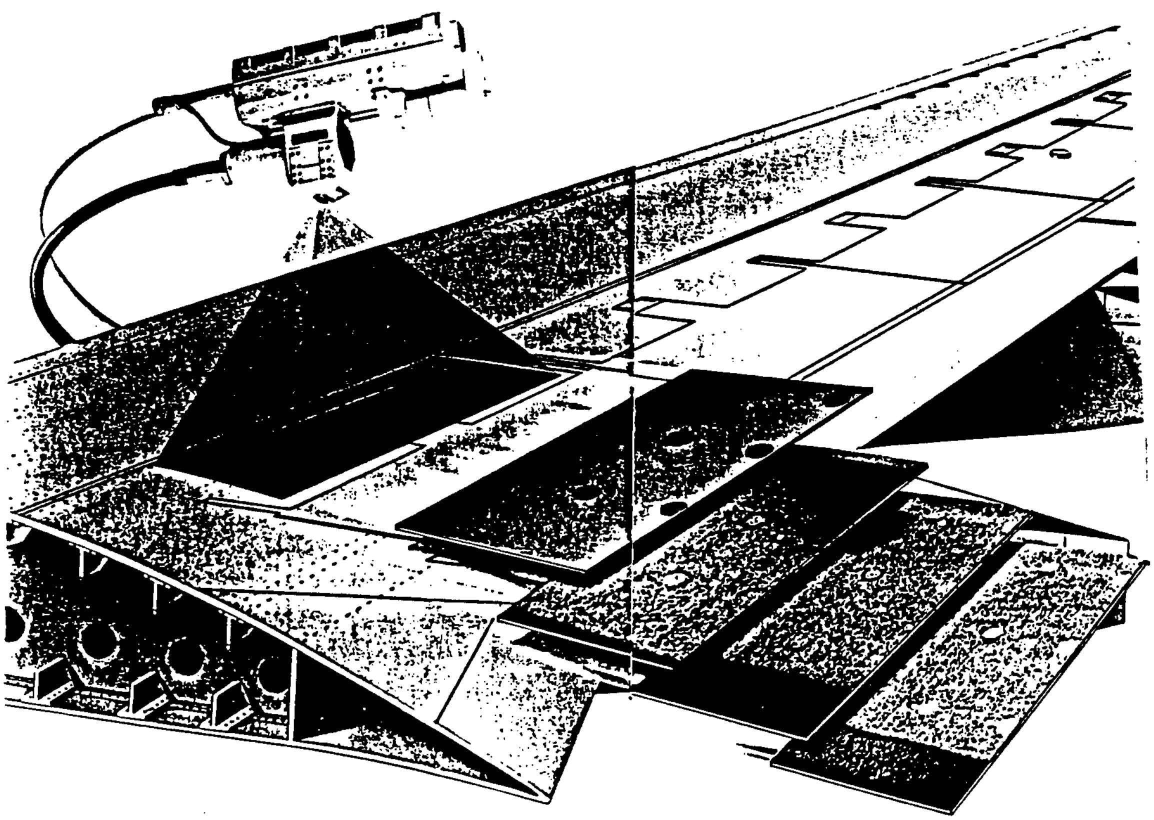


FIGURE 8. X-Ray Backscatter System

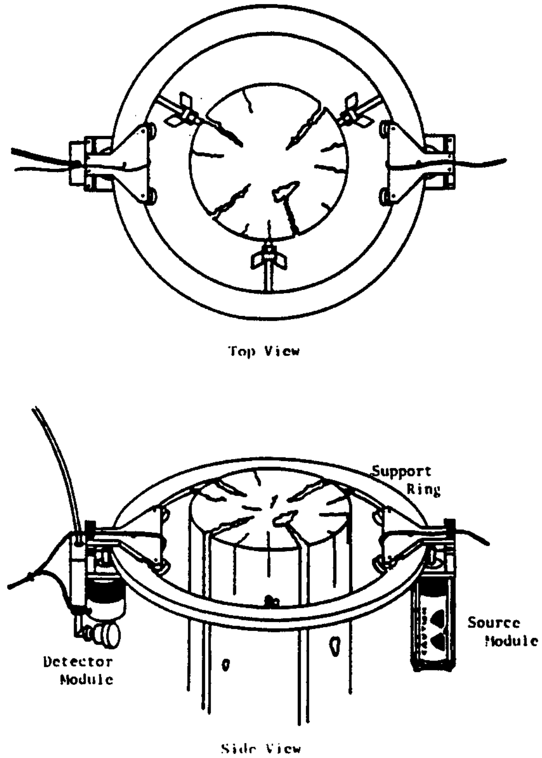


FIGURE 9. Sketch Portable CAT Scanner

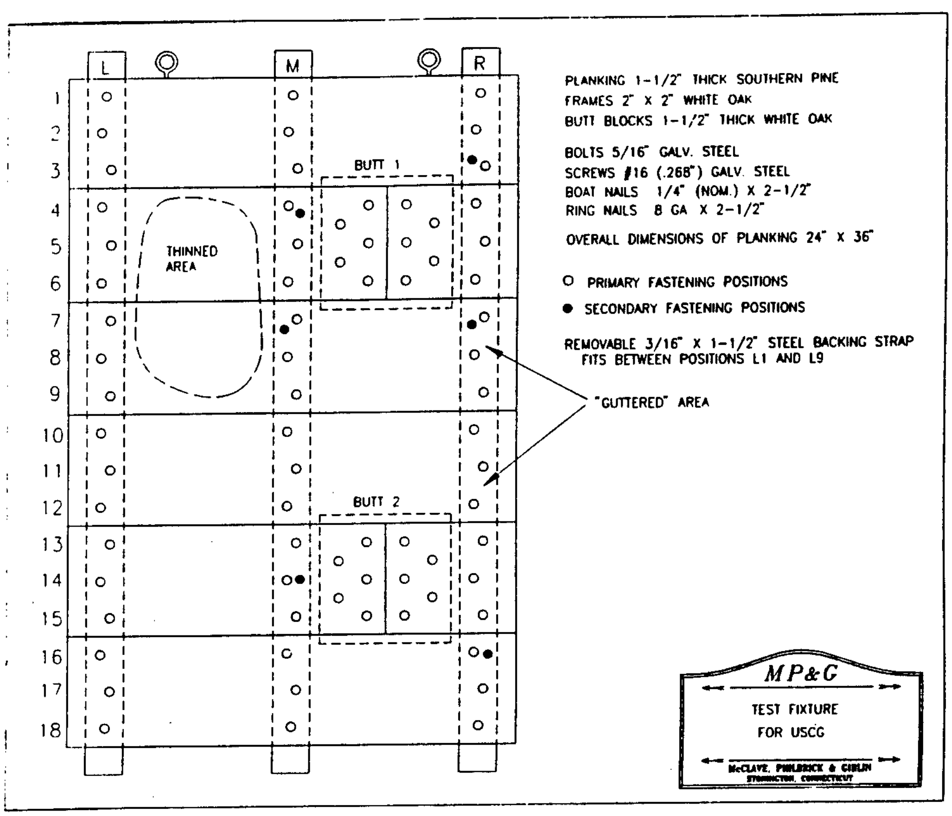


FIGURE 10. Test Fixture

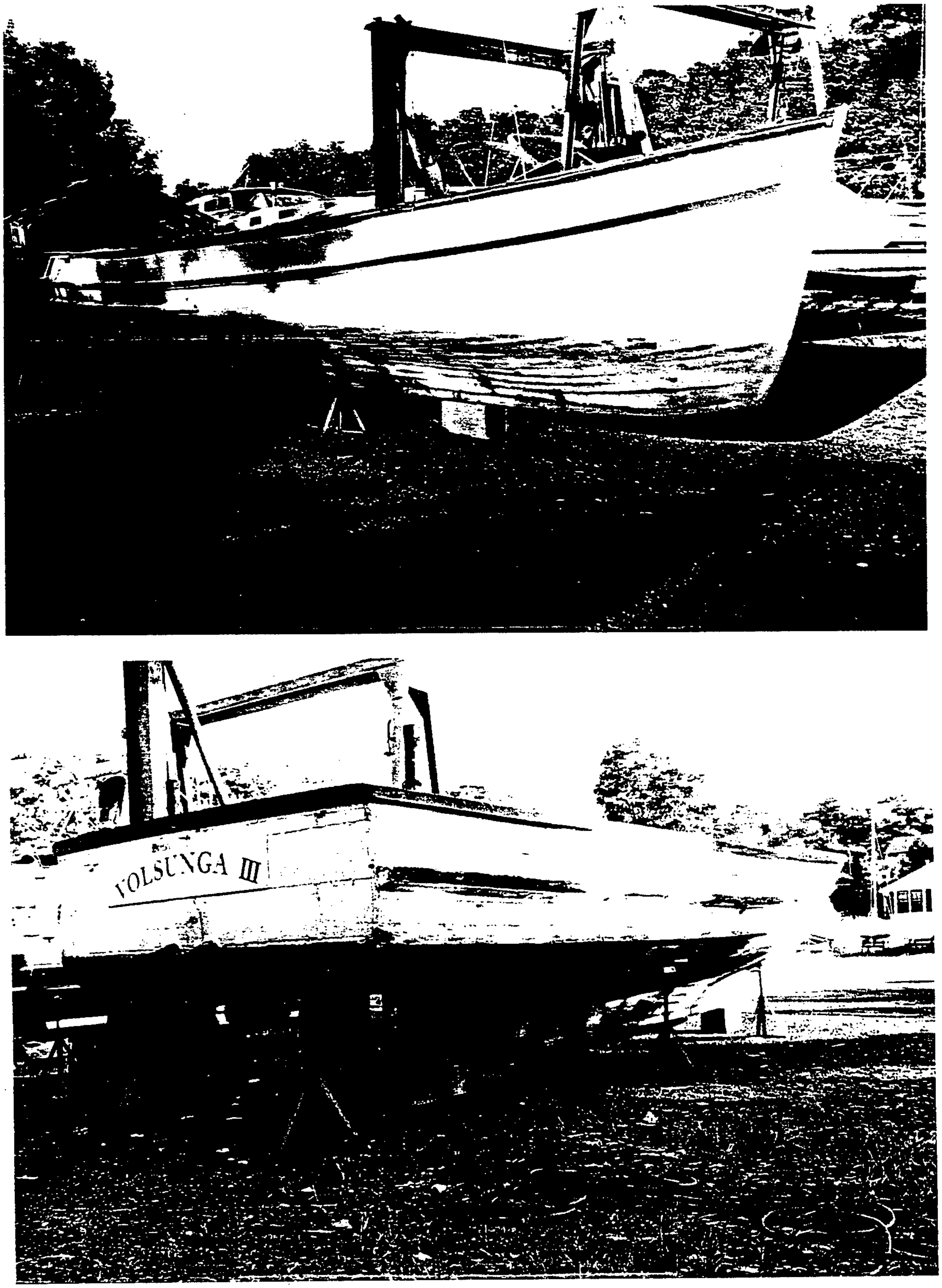


FIGURE 11. Views of Test Hull [15]

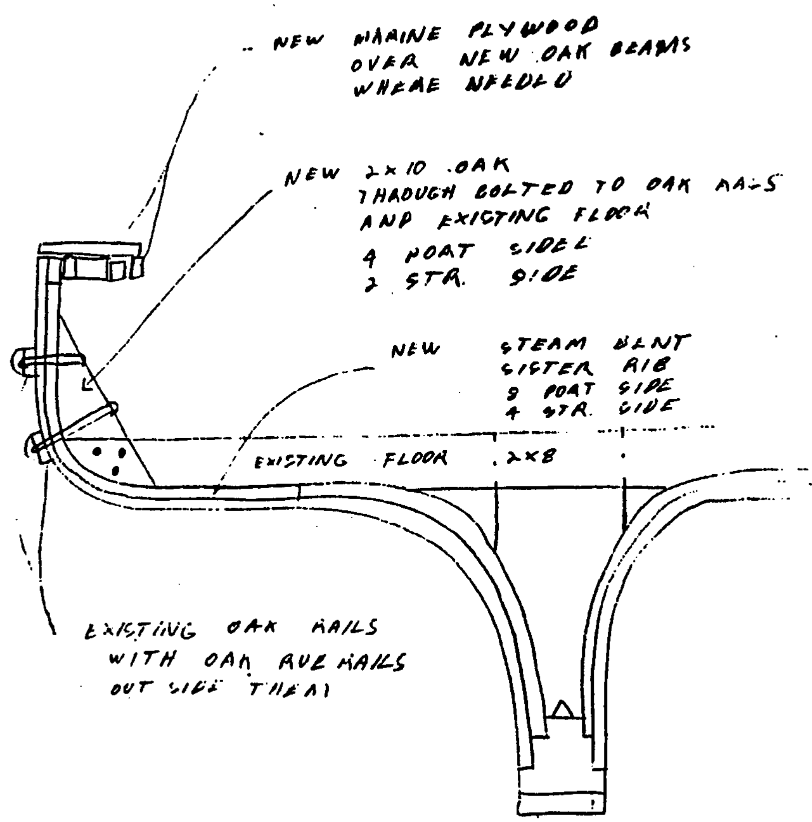


FIGURE 12. Sketch of Hull Modifications

FIGURE 13. Frames in Shaft Alley [15]

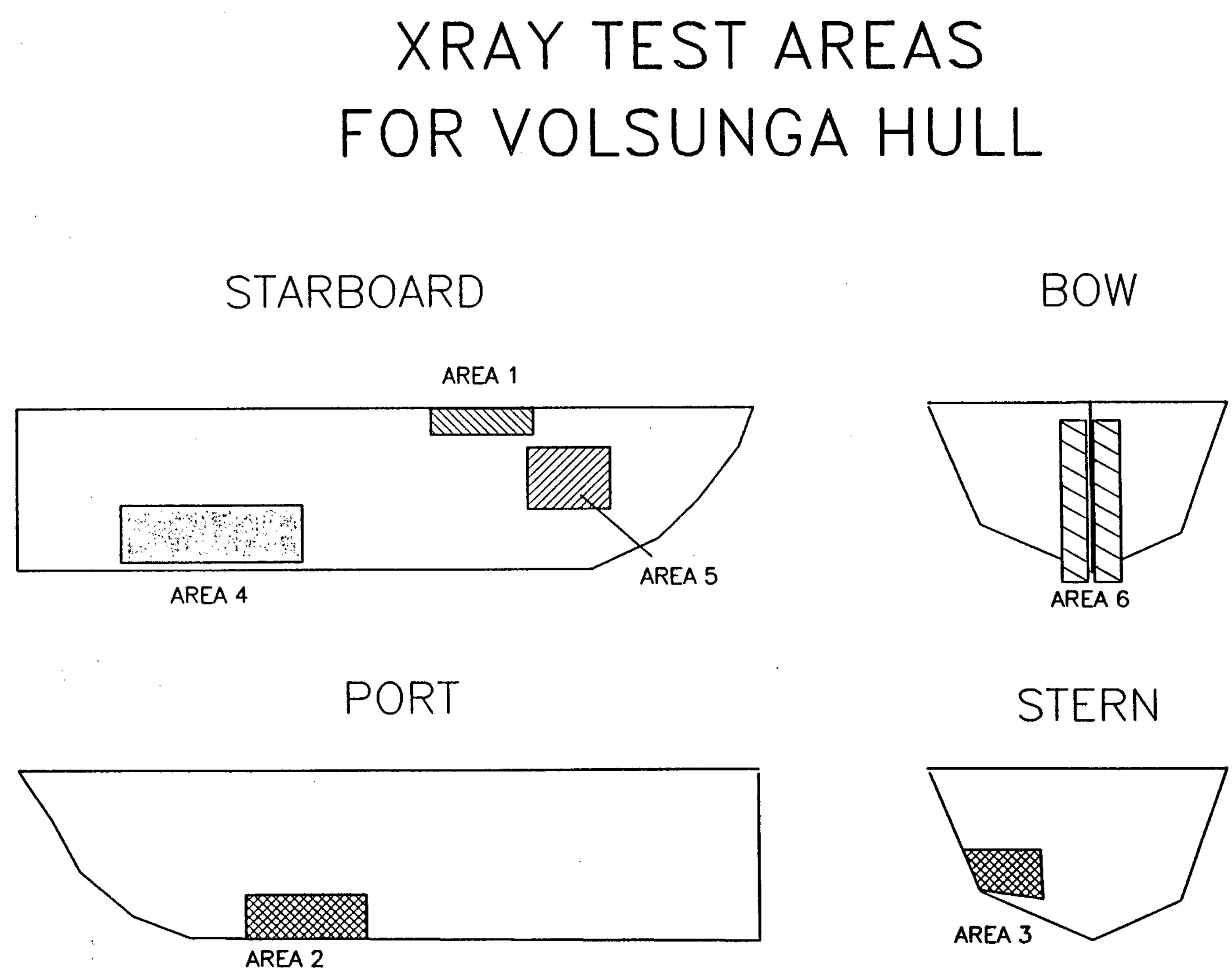


FIGURE 14. Test Area Locations

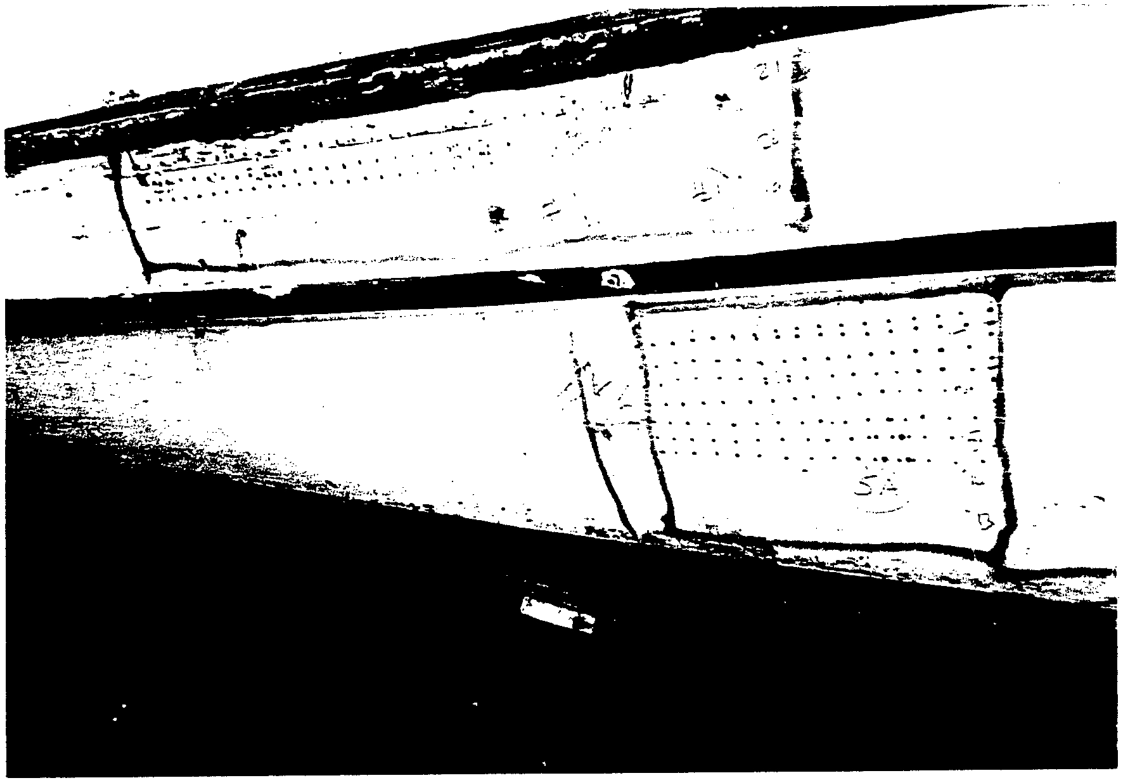


FIGURE 15. Photograph of Test Area 1

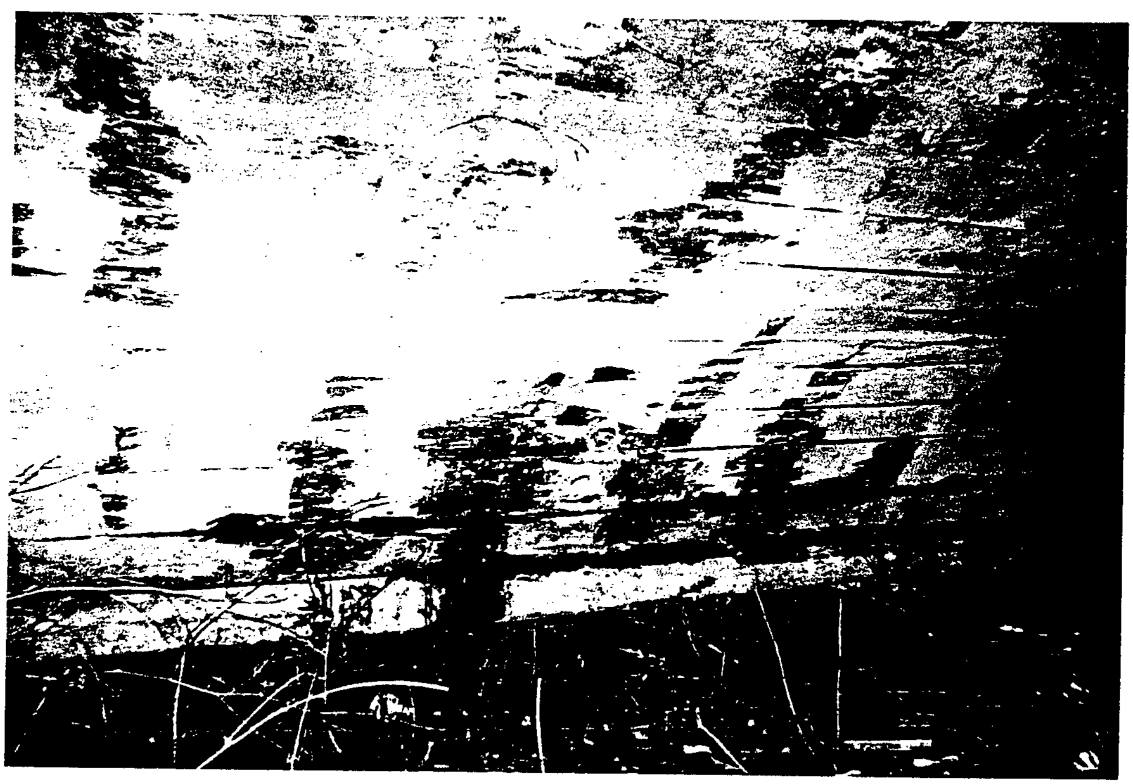


FIGURE 16. Photograph of Test Area 2

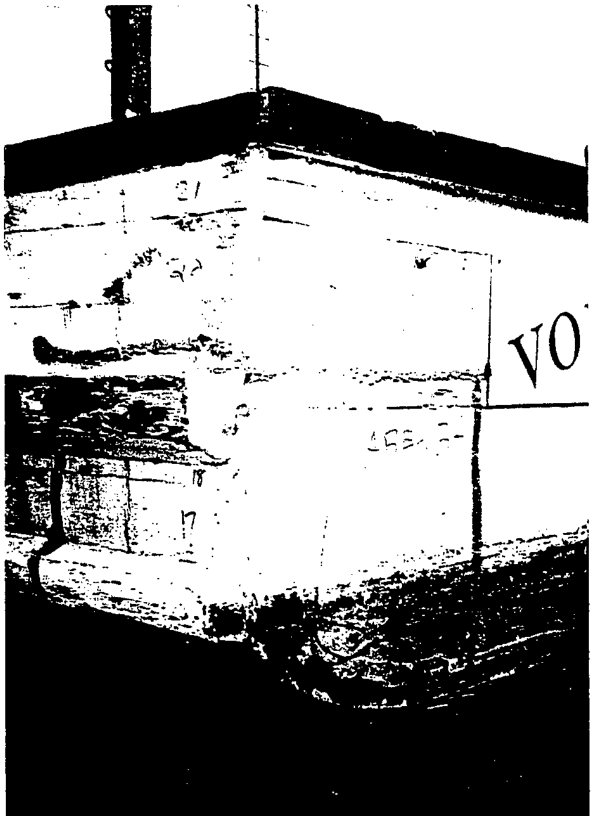


FIGURE 17. Photograph of Test Area 3

FIGURE 18. Photograph of Test Area 4

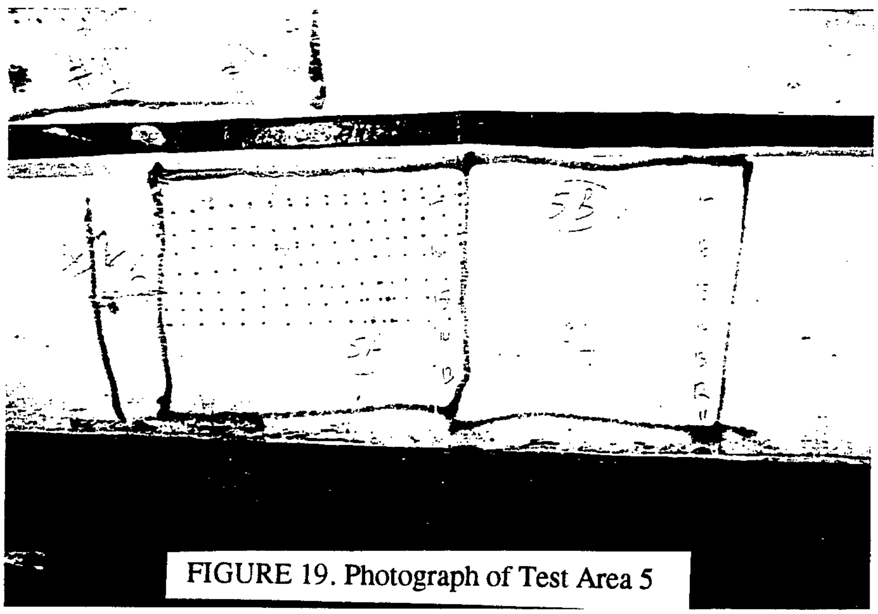


FIGURE 19. Photograph of Test Area 5

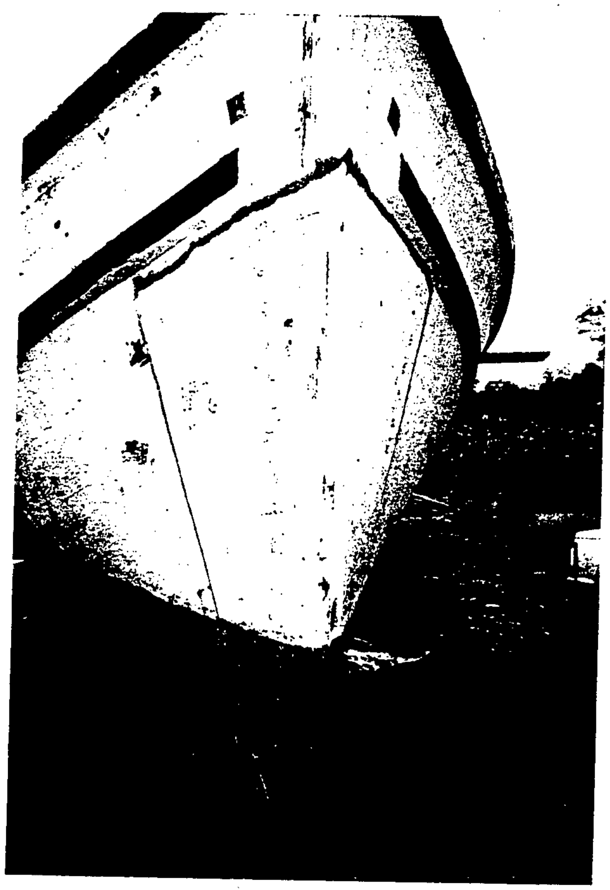
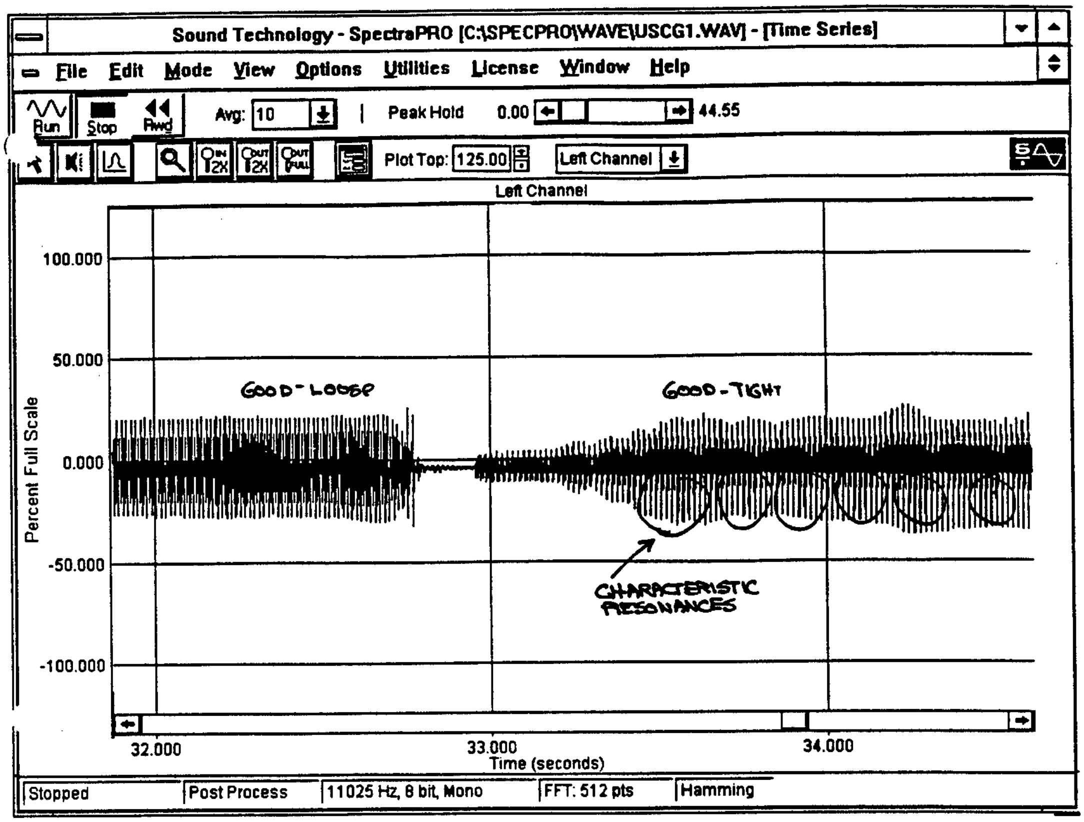


FIGURE 20. Photograph of Test Area 6



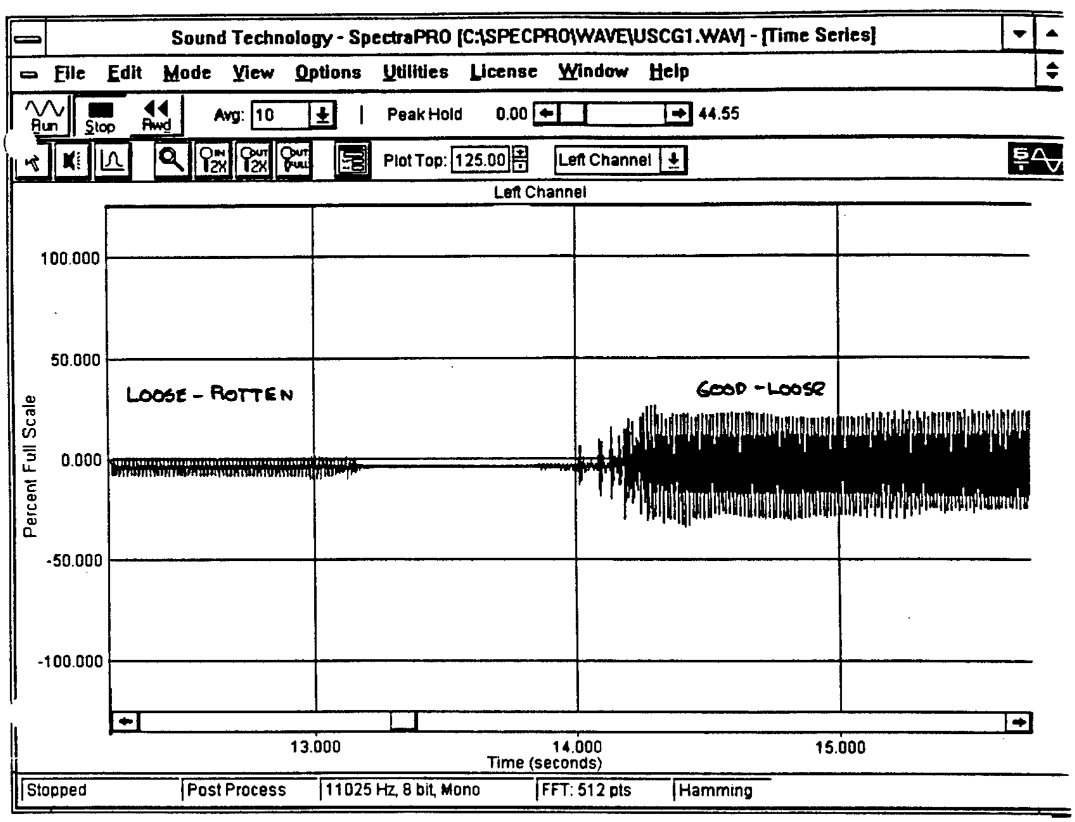


FIGURE 21. SMART HAMMER Results of Area 1

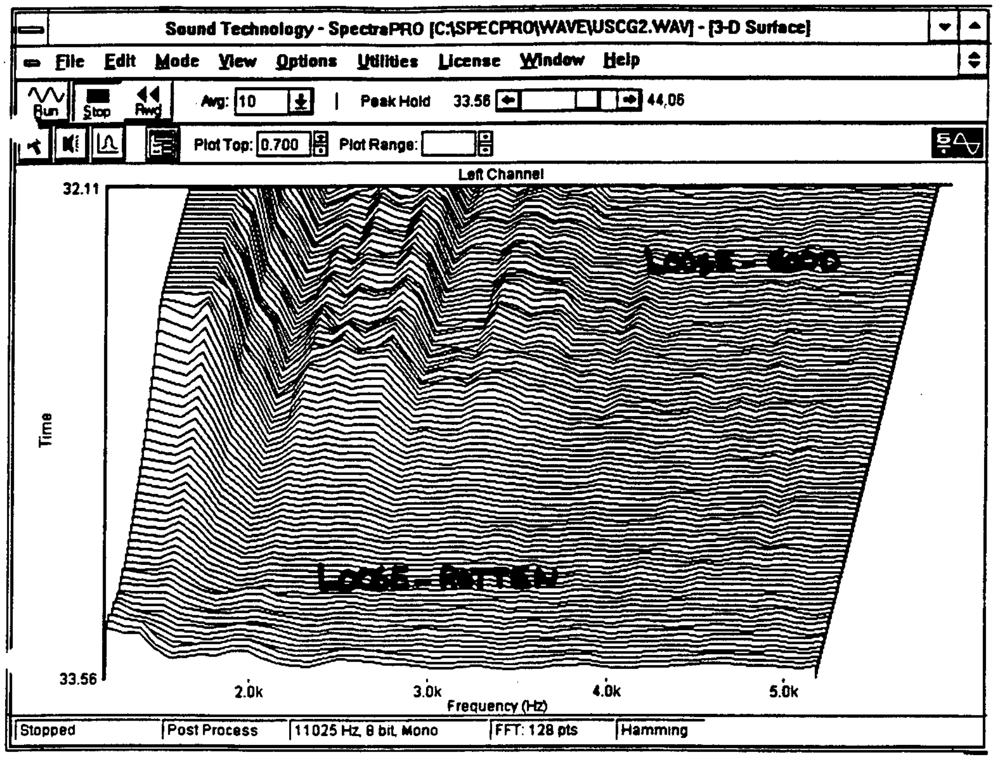


FIGURE 22. SMART HAMMER Results (3D Plot)

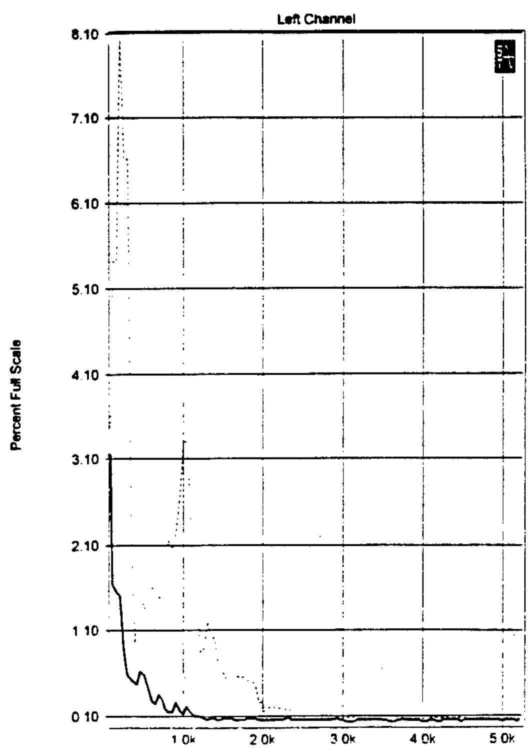


FIGURE 23. SMART HAMMER Results of good vs rotten areas
(dotted line = good plank, solid line = rotten area)

FIGURE 24. RESISTOGRAPH in Use

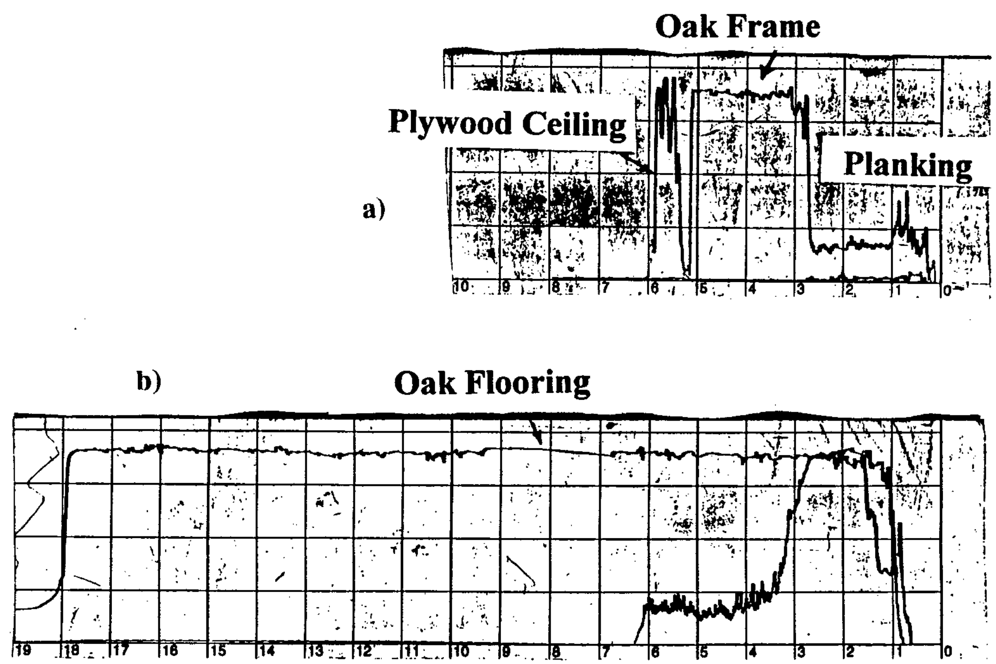


FIGURE 25. RESISTOGRAPH Results

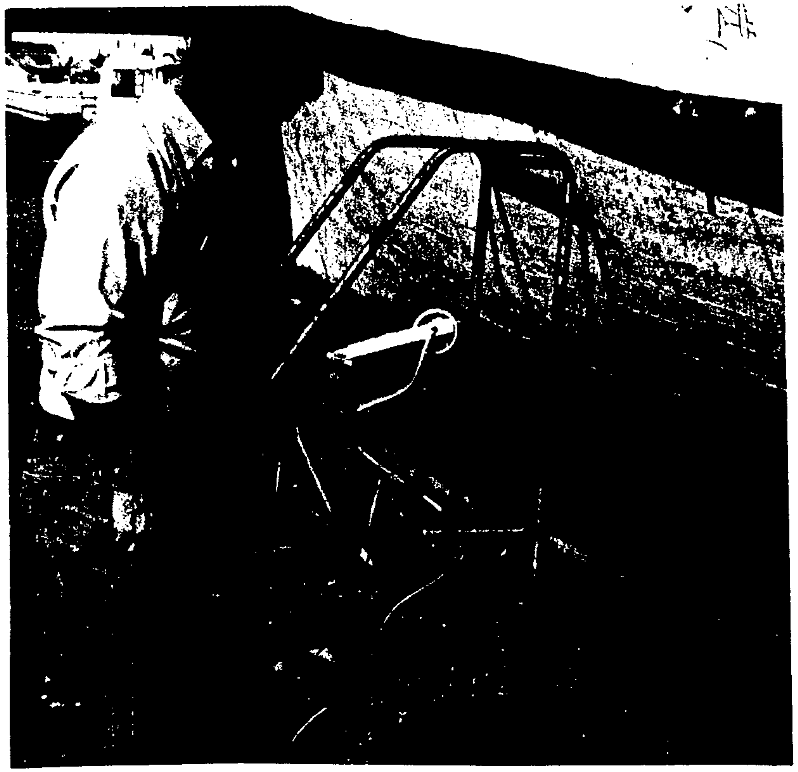


FIGURE 26. Capaciflector in Use

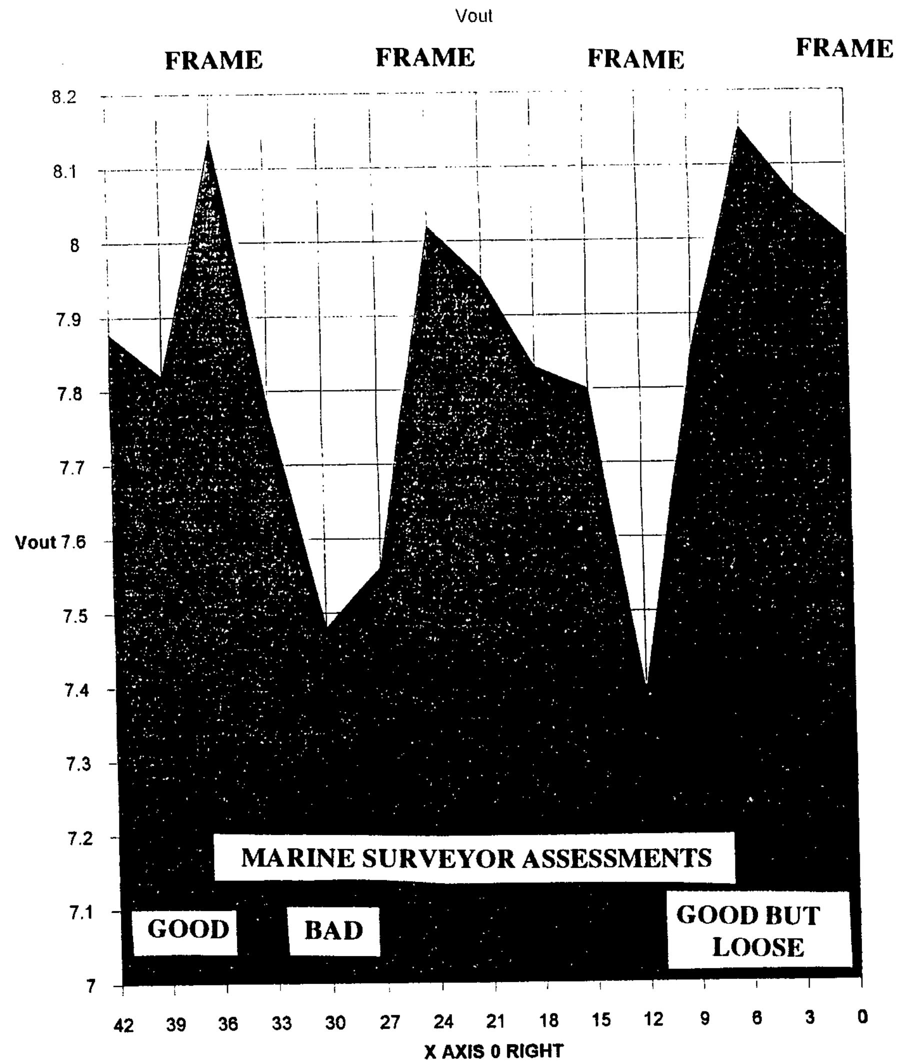


FIGURE 27. Capaciflector Results (Area 1)

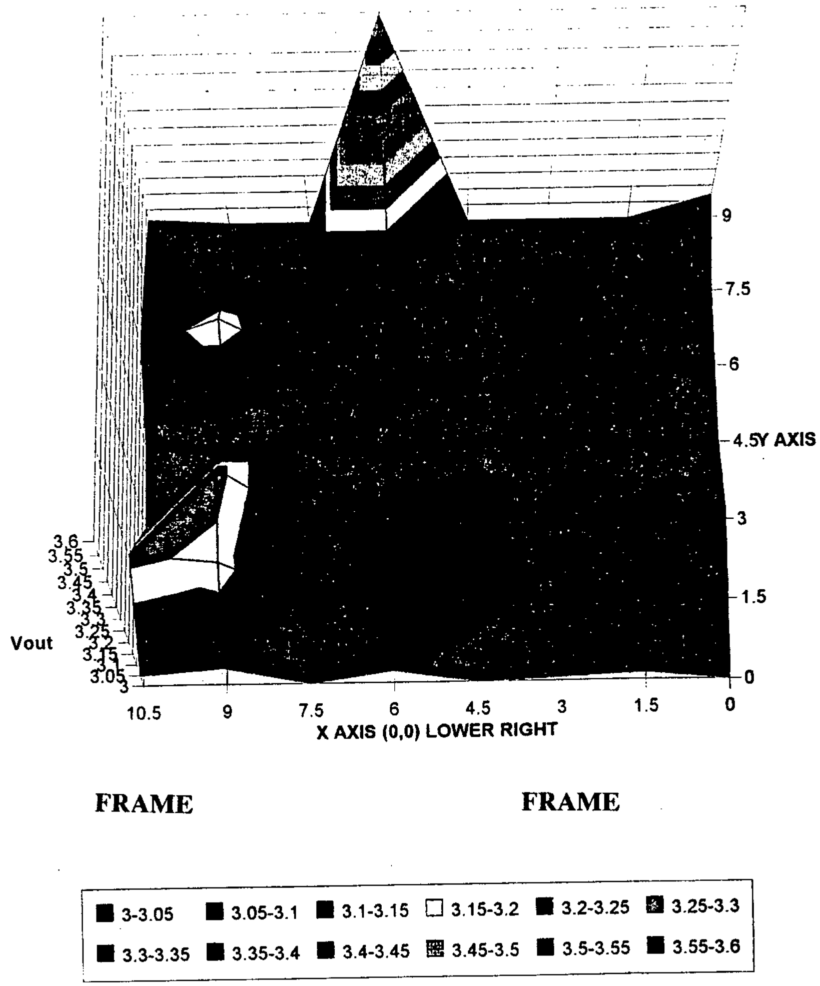


FIGURE 28. Capaciflector Results (Area 5)

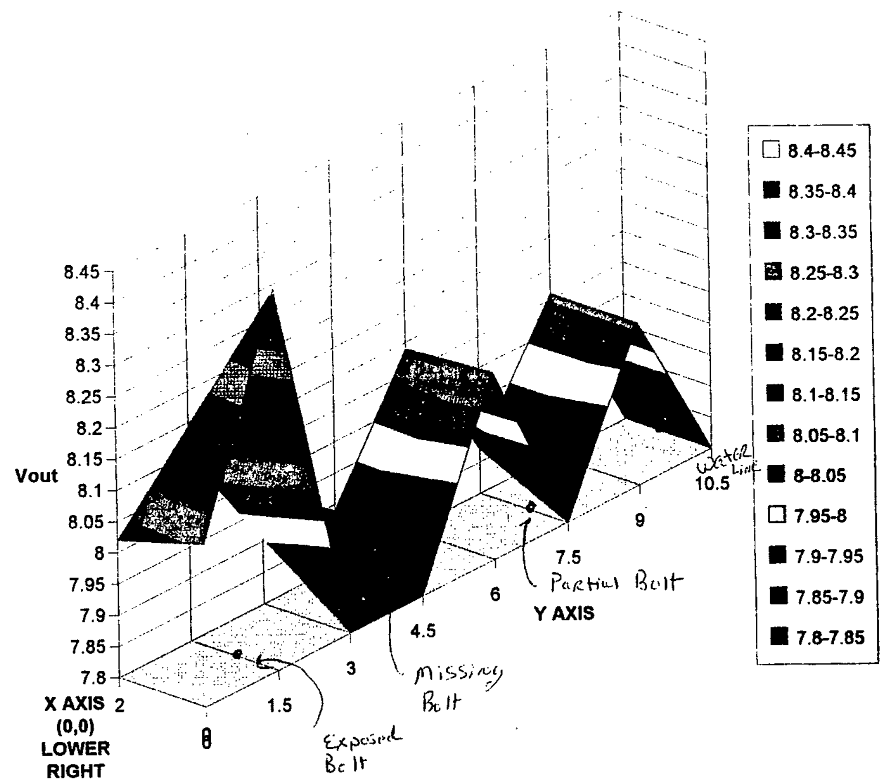


FIGURE 29. Capaciflector Results (Area 4)

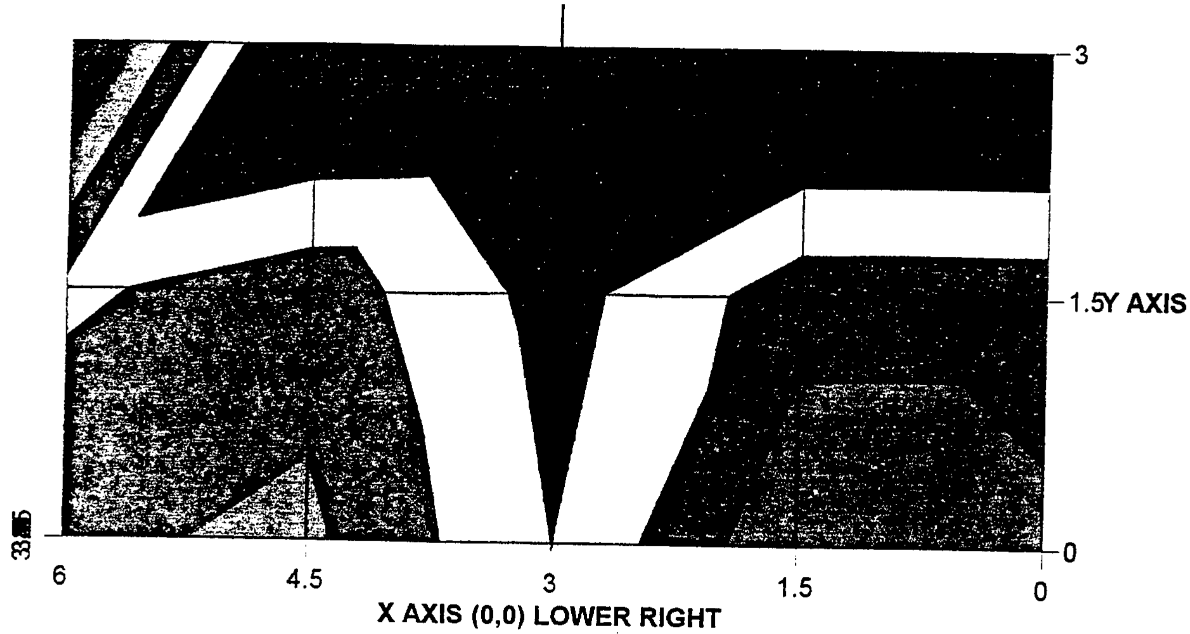


FIGURE 30. Capaciflector Results Questionable Joint

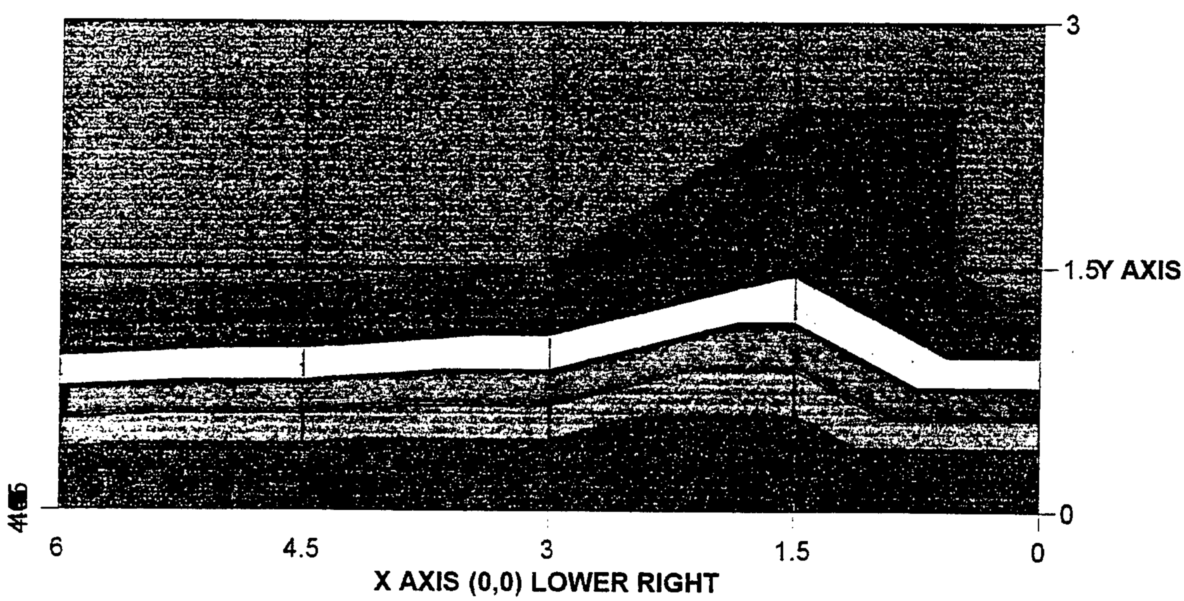


FIGURE 31. Capaciflector Results Good Joint

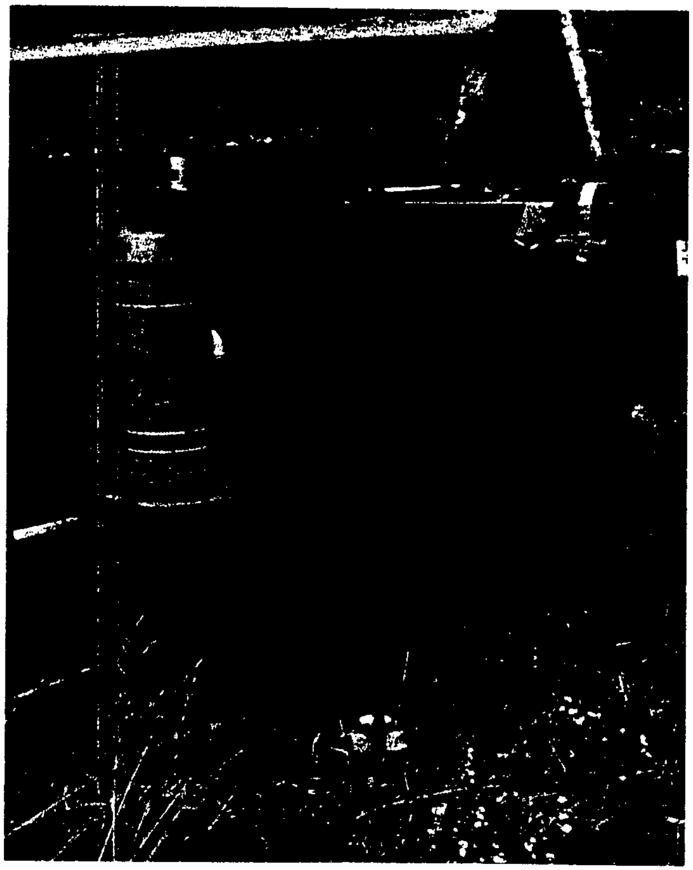


FIGURE 32. Conventional X-ray Source

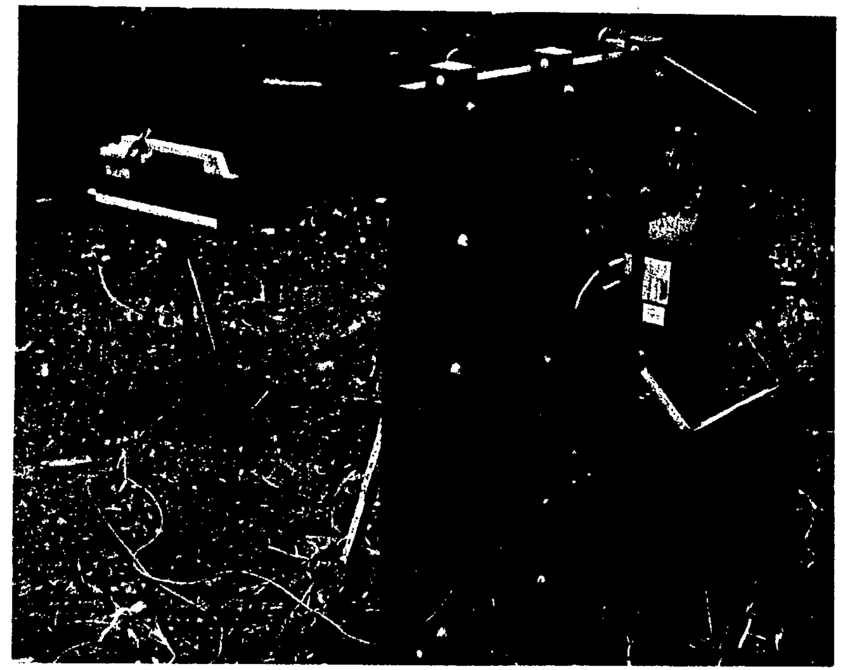
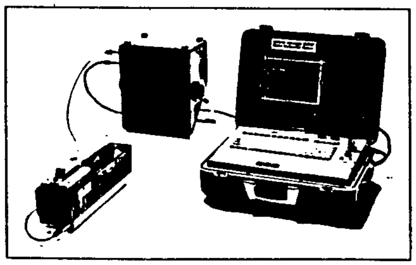


FIGURE 33. Real time X-ray System

Ultra Image DRS™

Portable Digital Radioscopy System

***Ultra Image DRS™* is a complete, one-person, portable system for real-time, digital, X-ray imaging of a wide range of NDE applications in the field**



- Instant images are enhanced and digitally stored on floppy or hard disk in TIFF format and transmittable via modem
- Image Processing - zoom, pan and scroll, contrast stretch, cursor measurement, sharpening and smoothing
- Safe operation; short nanosecond X-ray bursts (20-25 per second) with highly sensitive imager
- Portable, lightweight integrated control unit with 9.5-inch flat panel, high-brightness image display
- DRS™ is quick and easy to set up and operates from rechargeable batteries or AC power

Specifications

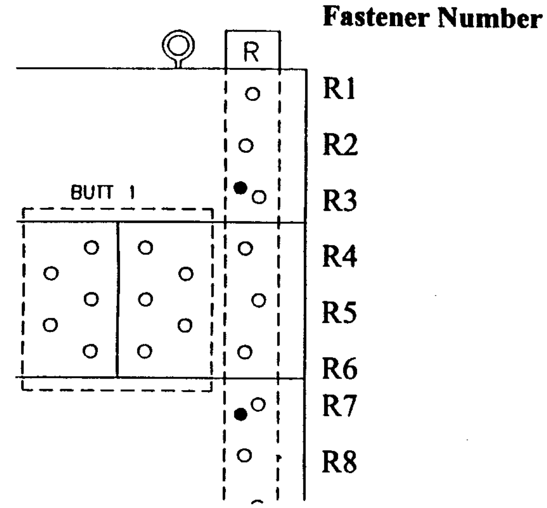
X-Ray Source:
- Pulsed X-ray source, 150 kV maximum energy, 0.5mA
- 3mRem output dose per pulse at one foot along beam centerline with 2.5mm aluminum filter
- Less than 30μRem dose per image acquisition 5 feet laterally away from source
- Laser pointers for beam alignment
- Rangefinder for automated source-to-object measurements
- Tripod mount
- Dimensions: 4.2"W x 4.2"D x 15"L; Weight: 20.5 lbs (with battery)
- Power: 115/230 VAC, 60 Hz, or self-contained 29V rechargeable battery pack

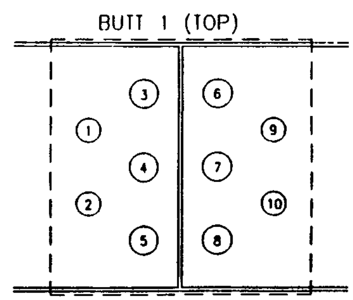
X-Ray Imager:
- 8 x 10-inch X-ray sensitive imaging screen
- Compact solid-state camera
- Tripod mount
- Dimensions: 10.3"W x 12"H x 7"D; Weight: 10 lbs
- Power: 12V provided by Control Unit

Control Unit:
- Portable PC with image processor, flat panel display, and interface electronics
- 486DX 66 MHz, 8Mb RAM, 852Mb HD, 3.5" floppy, 28.8 kbaud modem
- Dimensions: 18"W x 13"D x 7"H; Weight: 25 lbs (with battery)
- Power: 115/230 VAC, 60Hz, or self-contained 12V rechargeable battery pack

Accessories:
- 60-foot cable between Control Unit and Imager (optional 60-foot extensions)
- 10-foot cable between Imager and Source (optional 10-foot extensions or optional RF trigger requiring no cables)
- Tripods to support X-Ray Source and Imager
- Optional Scanners to image large areas
- Optional Remote Handling Package

FIGURE 34. Real-Time System Specifications





FASTENING POSITION	FASTENING TYPE	DEFECT TYPE
T1	SCREW	S2
T2	SCREW	-
T3	BOLT	-
T4	BOLT	B1
T5	BOLT	B2
T6	BOLT	B2
T7	BOLT	-
T8	BOLT	B1
T9	SCREW	S1
T10	SCREW	-

FIGURE 35. Test Fixture Details

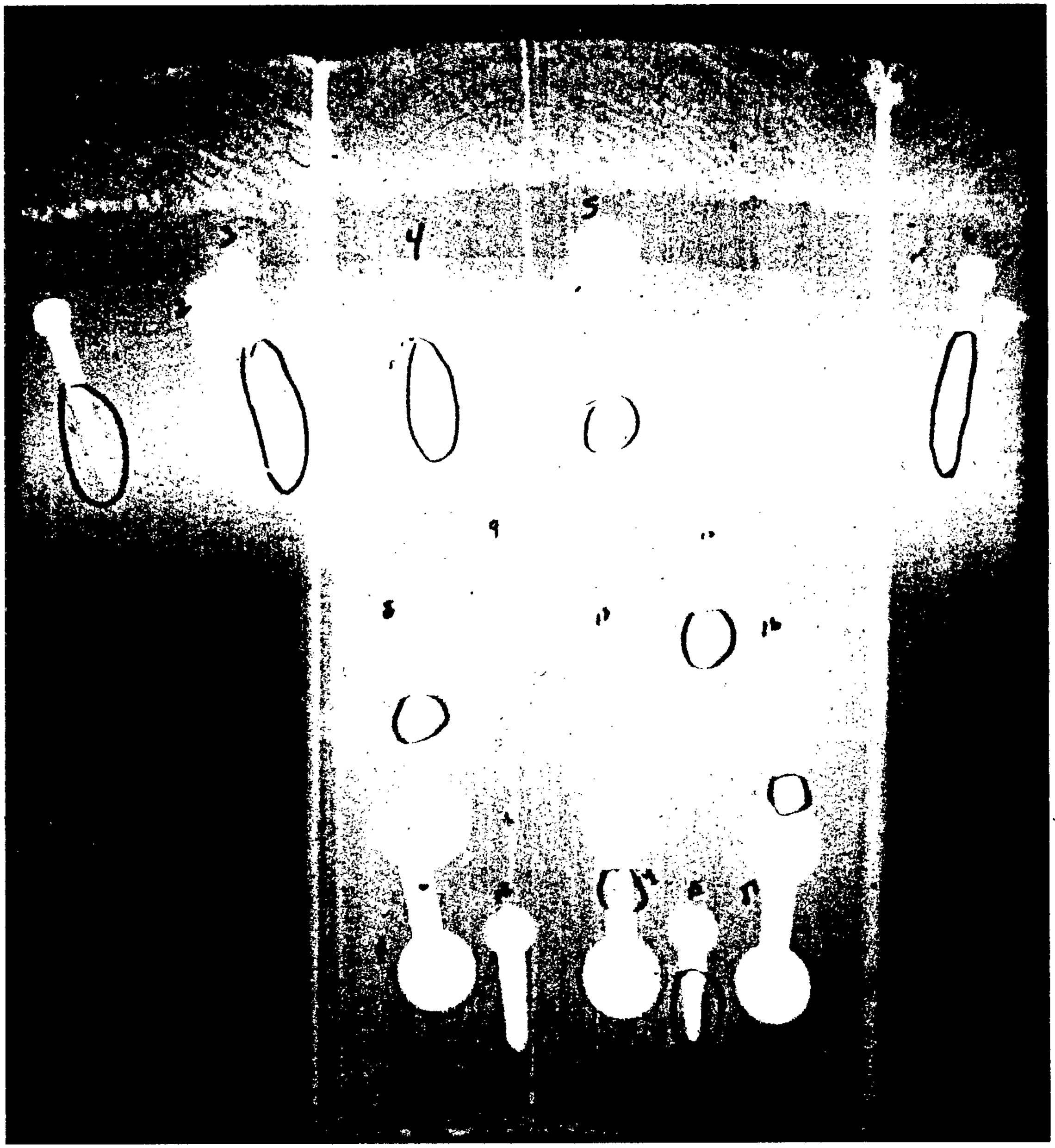


FIGURE 36. Conventional X-ray of Test Fixture

Number on X-Ray	Test Fixture Number
1	R8
2	R7
3	R7
4	R6
5	R5
6	R3
7	R3
8	T8
9	T10
10	T9
11	T5
12	T2
13	T7
14	T4
15	T1
16	T6
17	T3

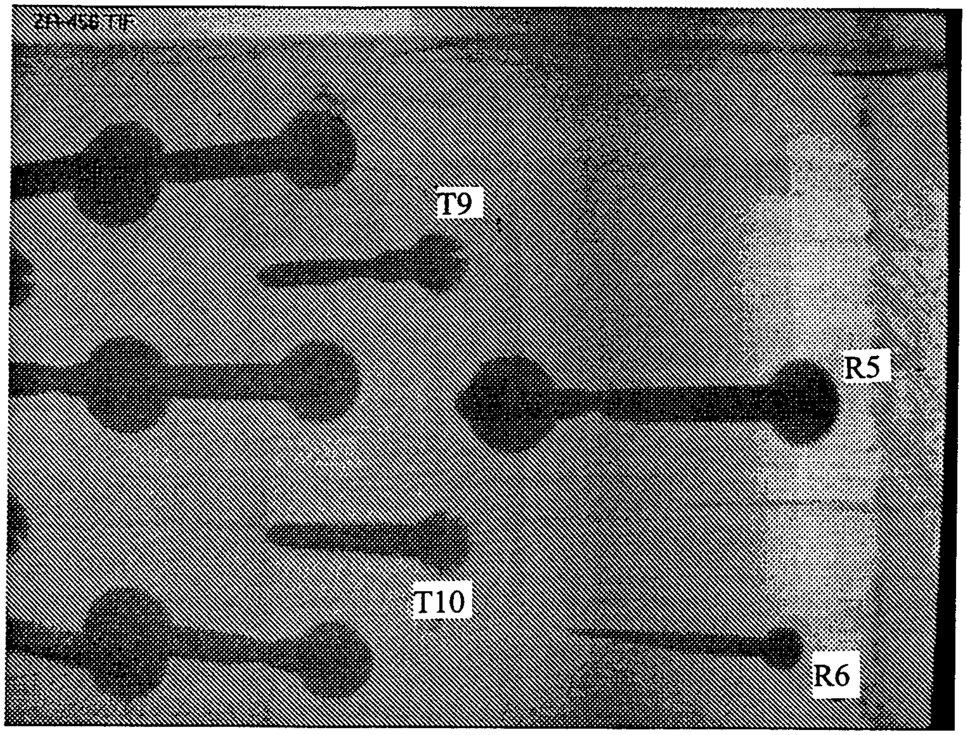


FIGURE 37. Real time X-ray of Test Fixture

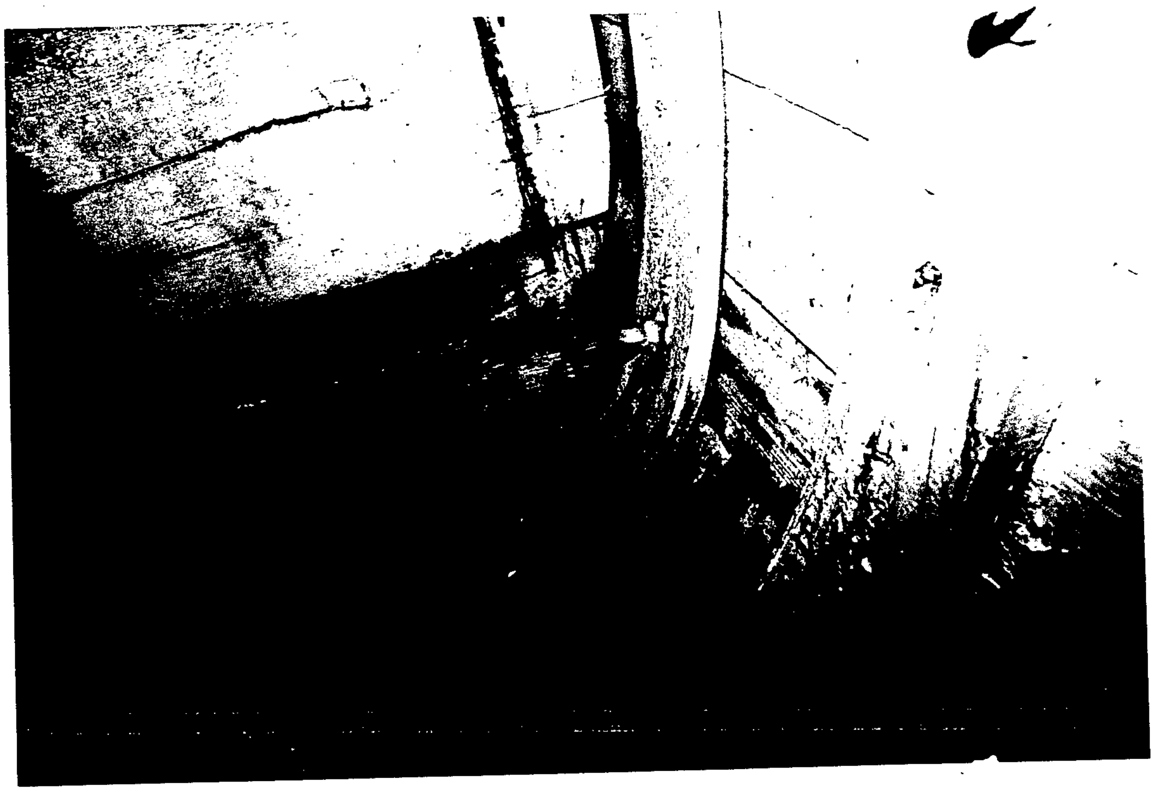


FIGURE 38. Photograph of inside stern[15]

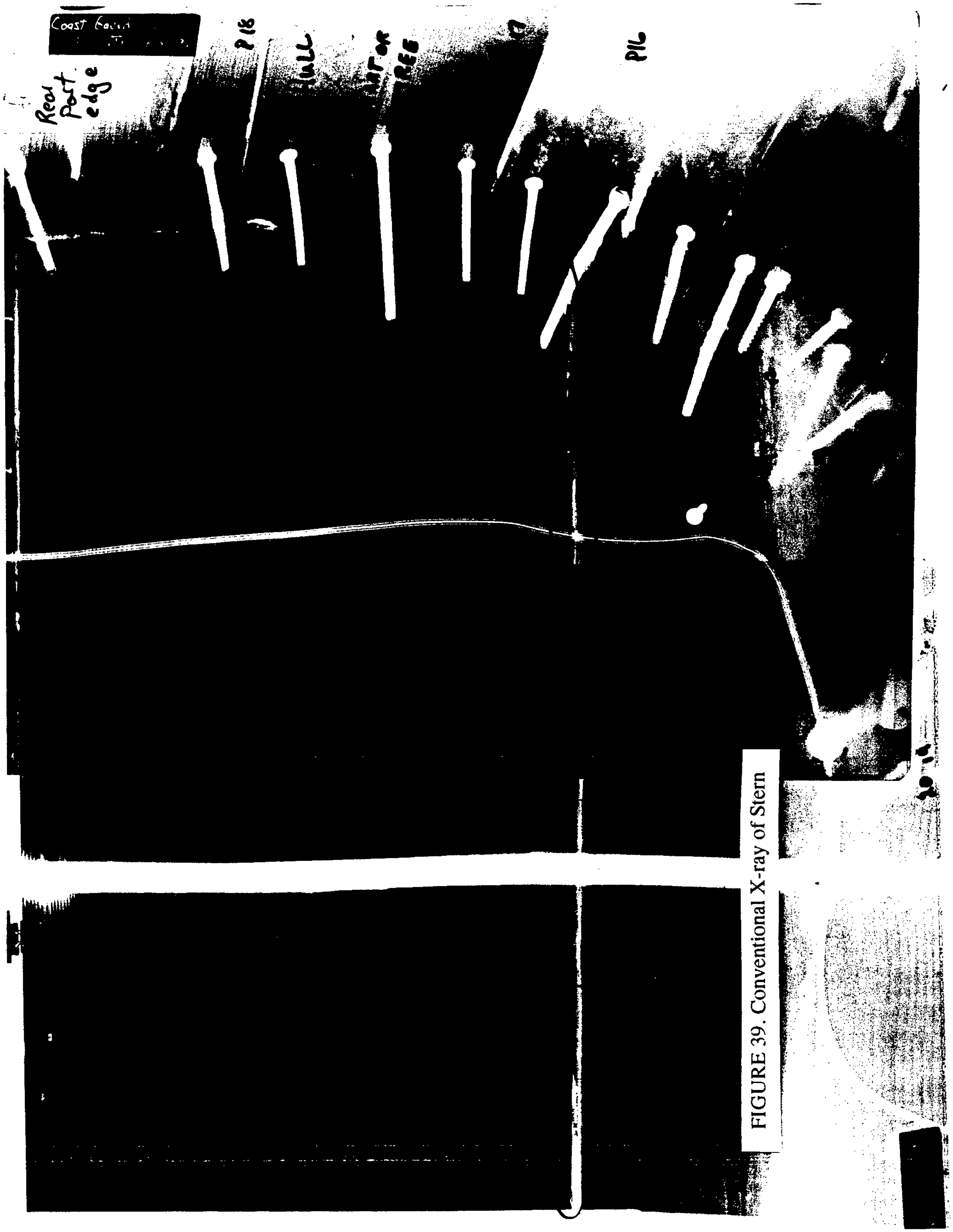


FIGURE 39. Conventional X-ray of Stern

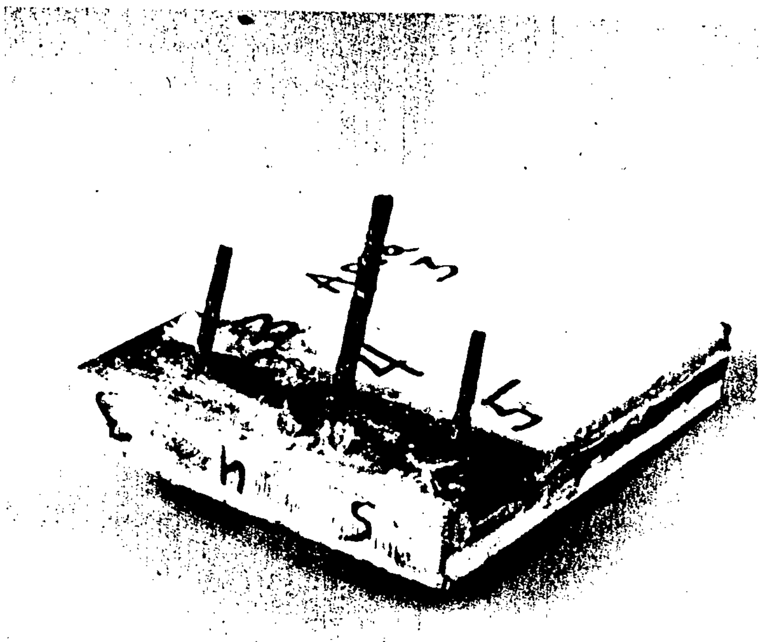


FIGURE 40. Photograph of Fasteners 3,4 and 5 in Area 3

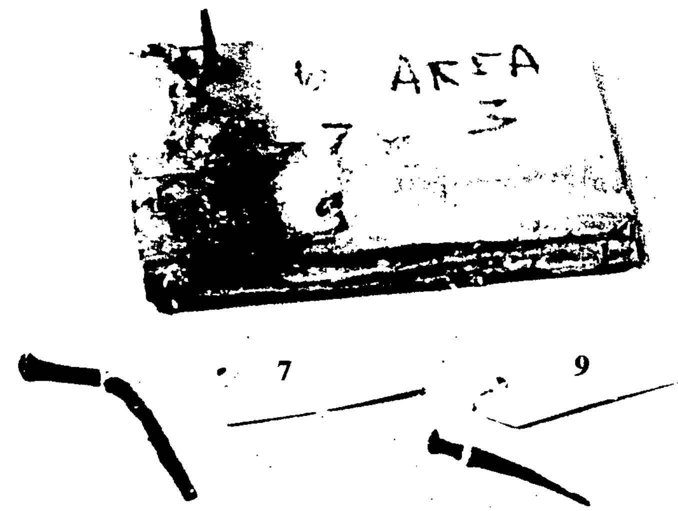


FIGURE 41. Photograph of Fasteners 6, 7 and 9 in Area 3

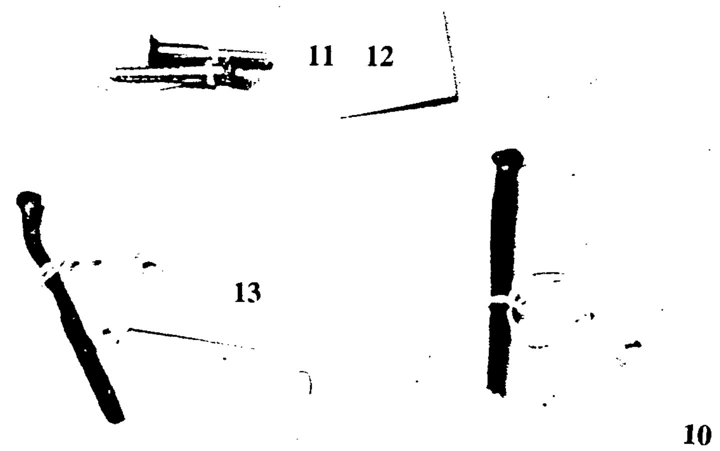


FIGURE 42. Photograph of Fasteners 10, 11, 12 and 13 in Area 3

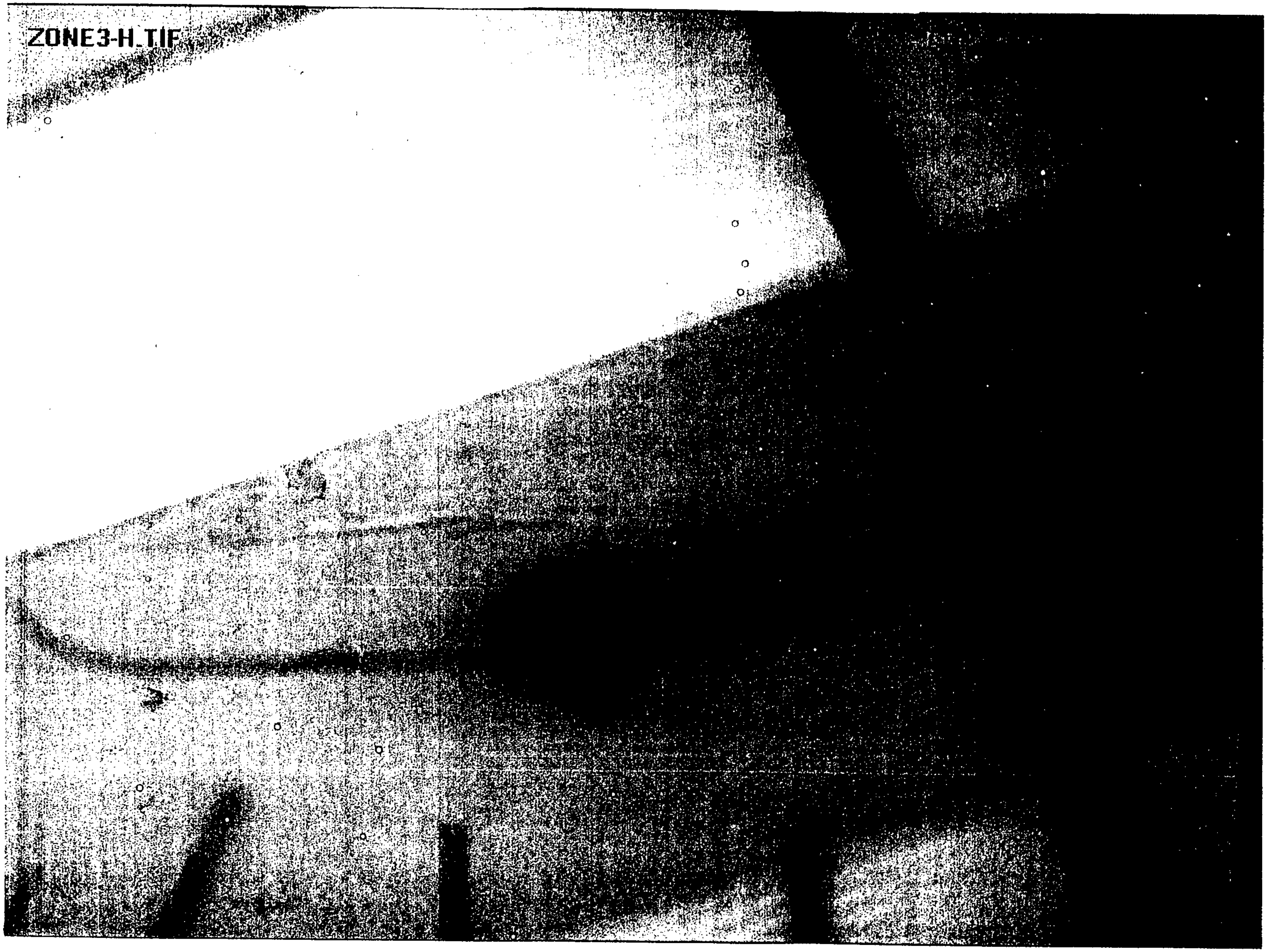


FIGURE 43. Real time Perpendicular Shot in Area 3

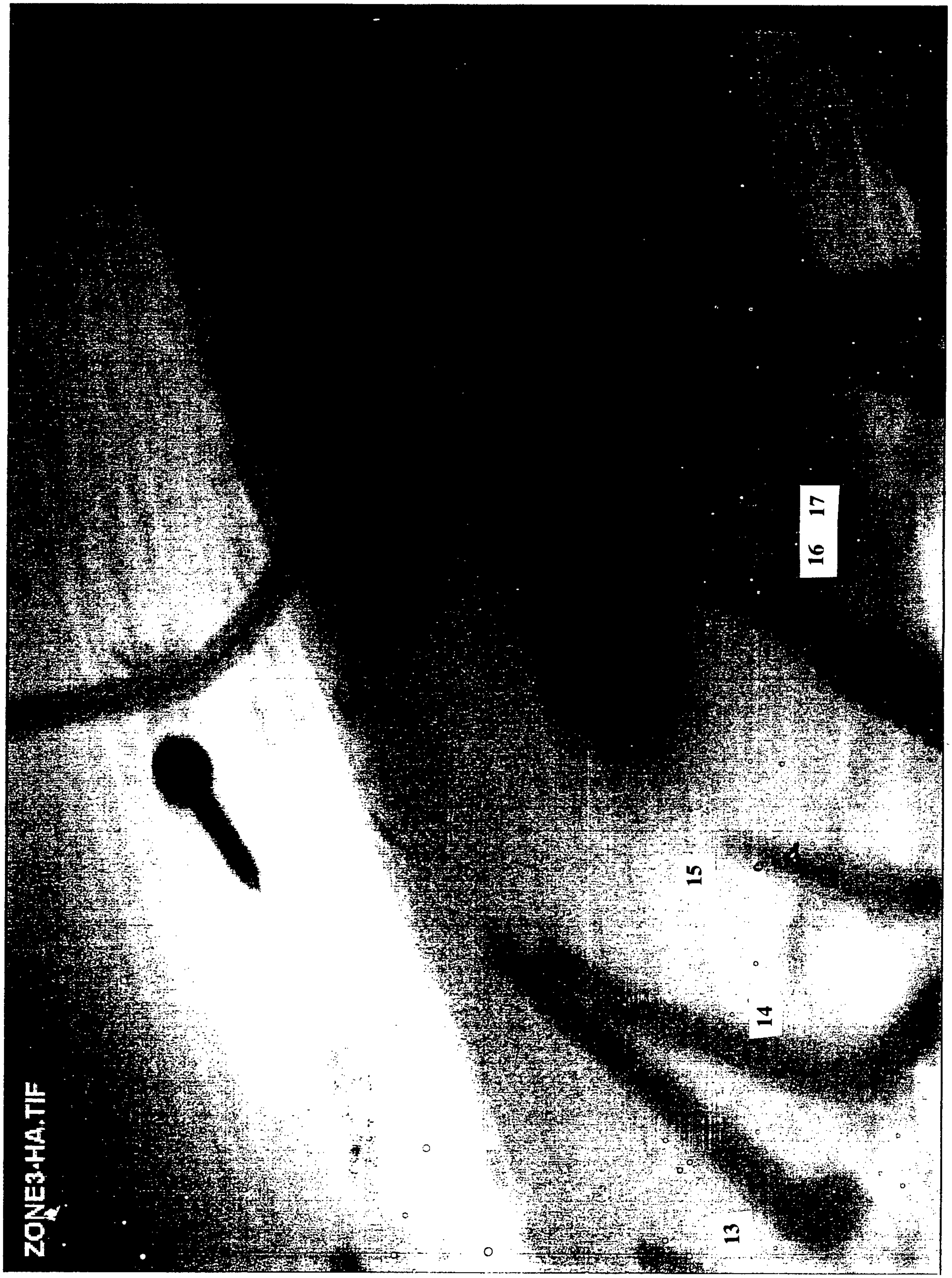


FIGURE 44. Real time Angled Shot in Area 3

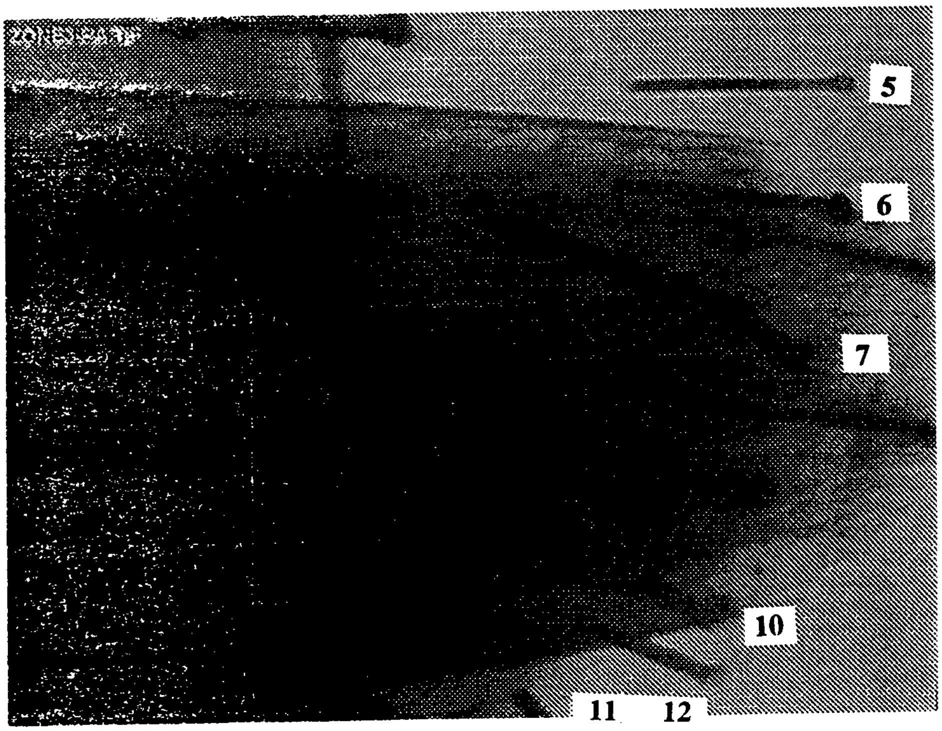


FIGURE 45. Real time Shot Through corner in Area 3

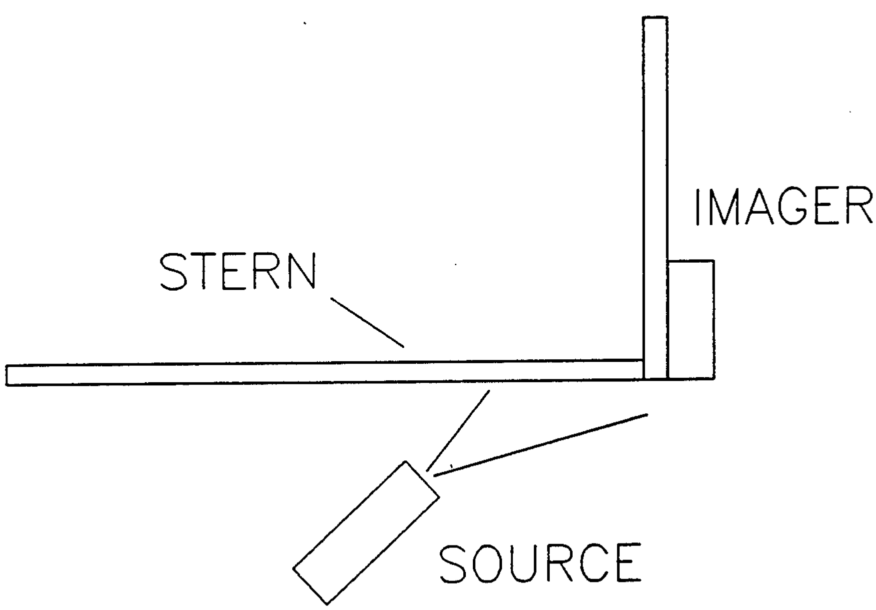


FIGURE 46. Diagram of Stern Corner shot

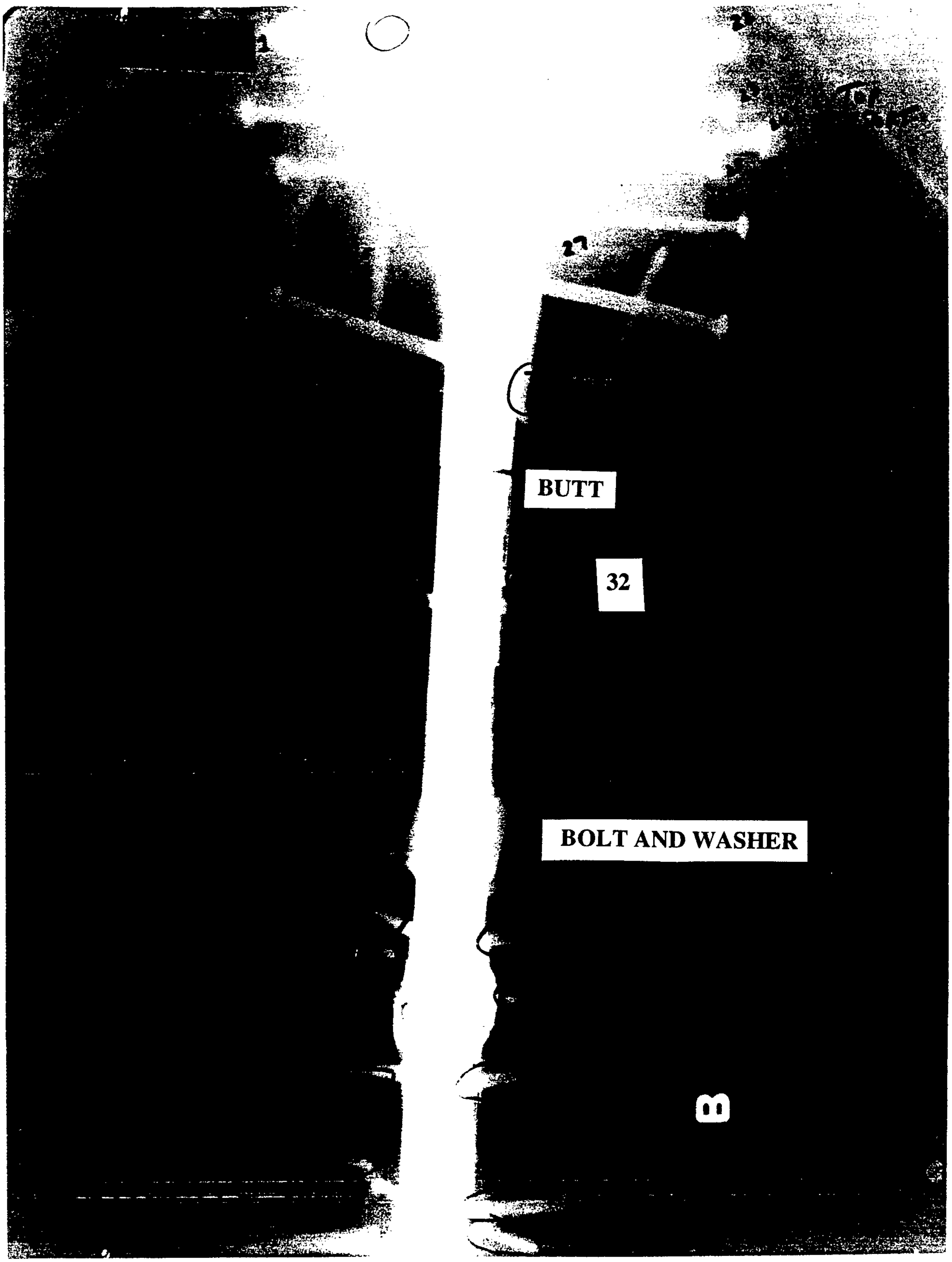


FIGURE 47. Conventional X-ray of Stem

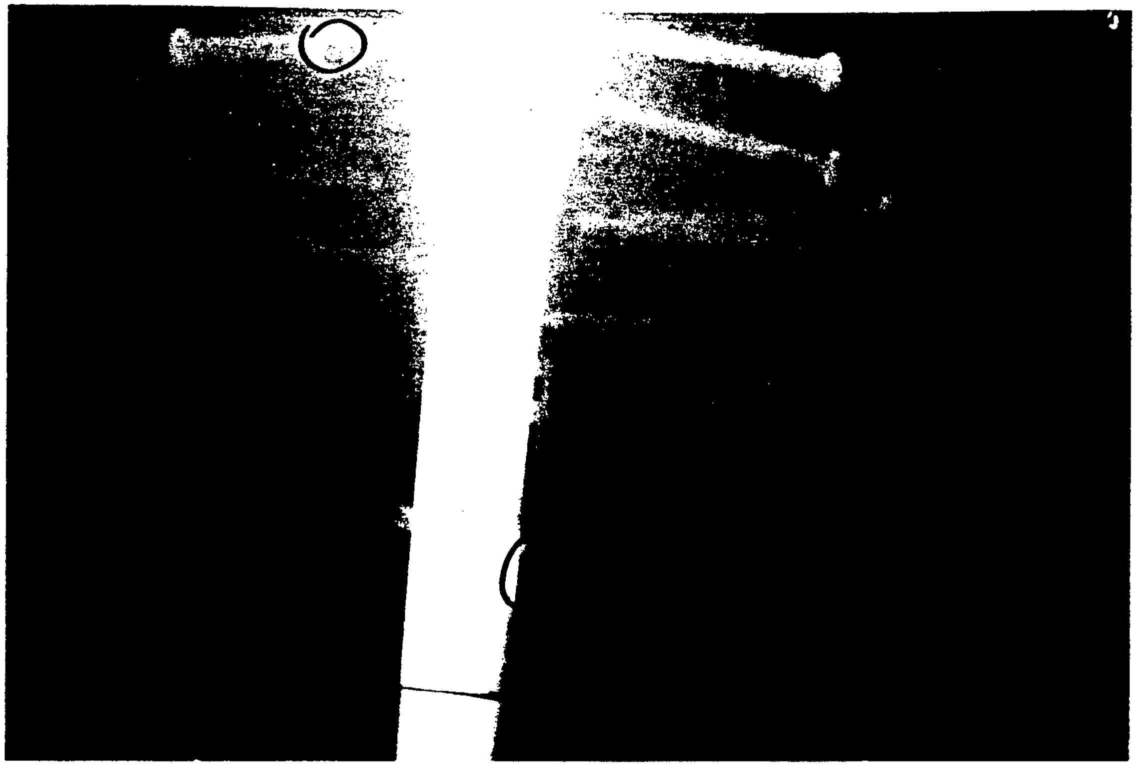


FIGURE 48. Close-up of Top of Stem X-ray

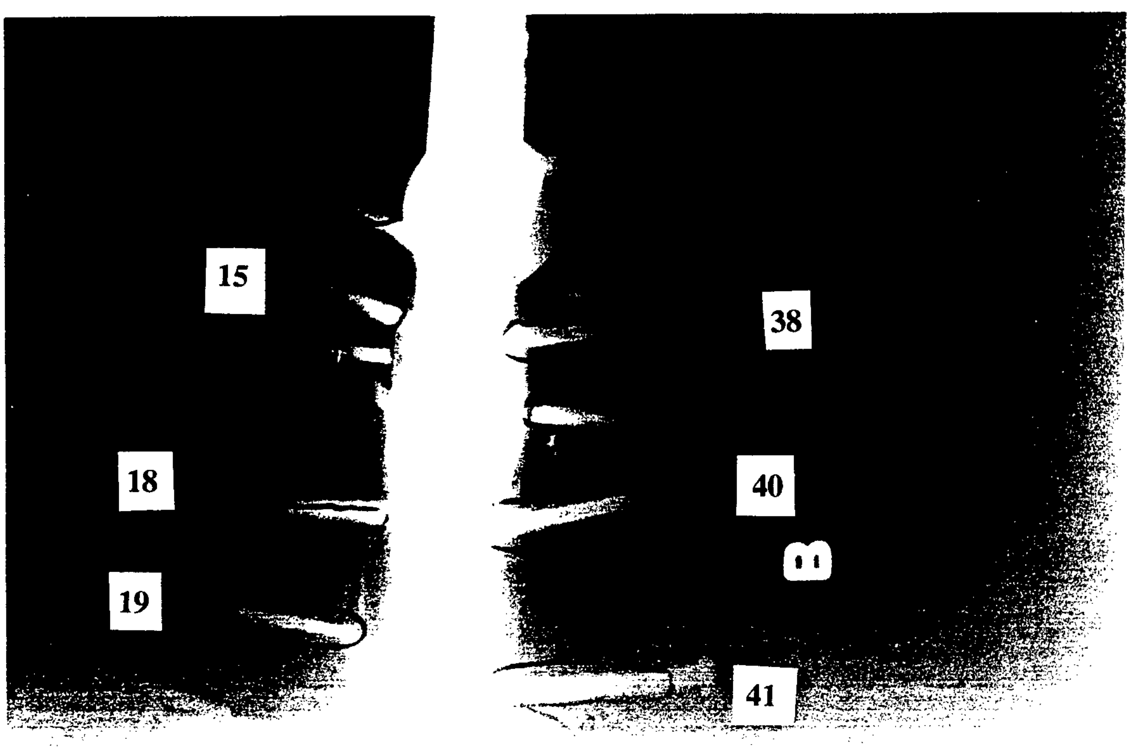


FIGURE 49. Close-up of Bolt Area

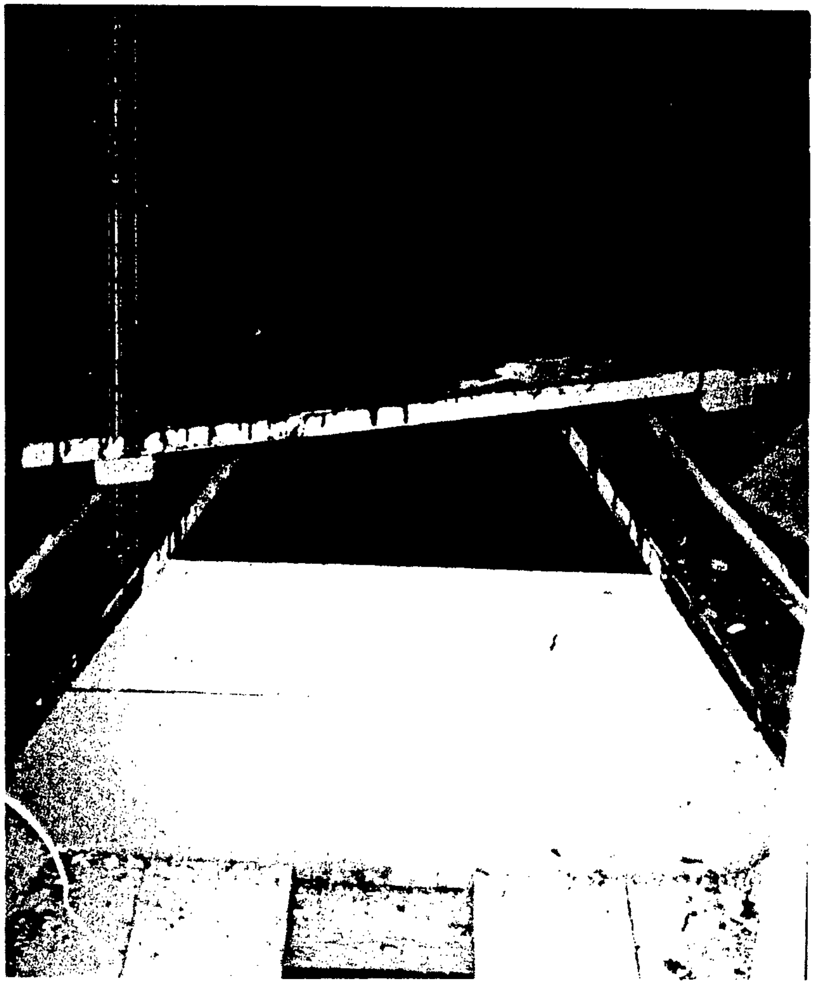


FIGURE 50. Photograph inside cabin at bow

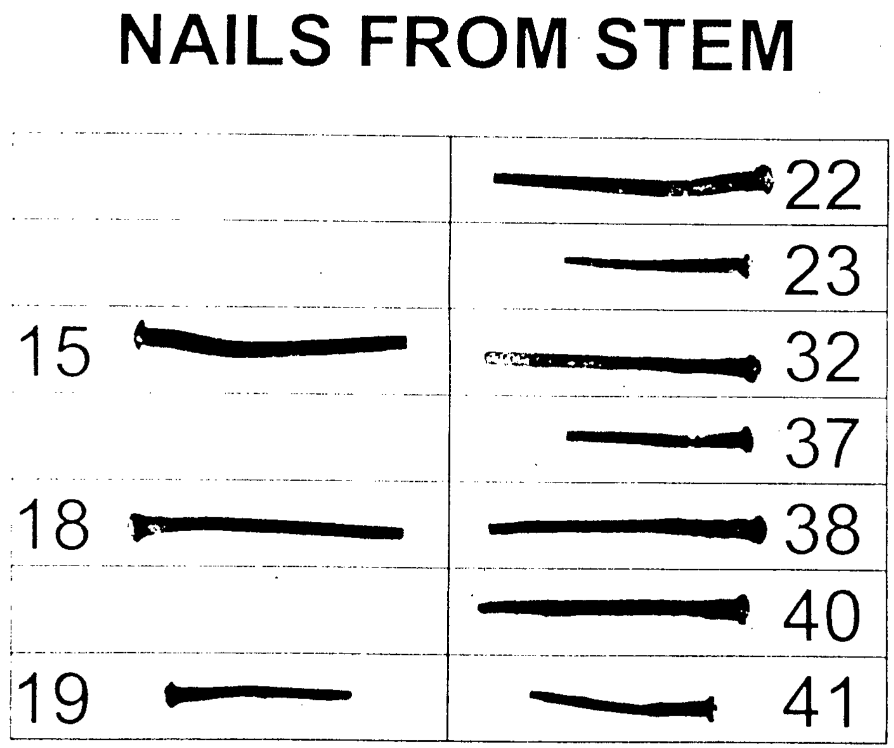


FIGURE 51. Picture of Stem Fasteners

FIGURE 52. Real Time shot of stem at 40 inches from deck

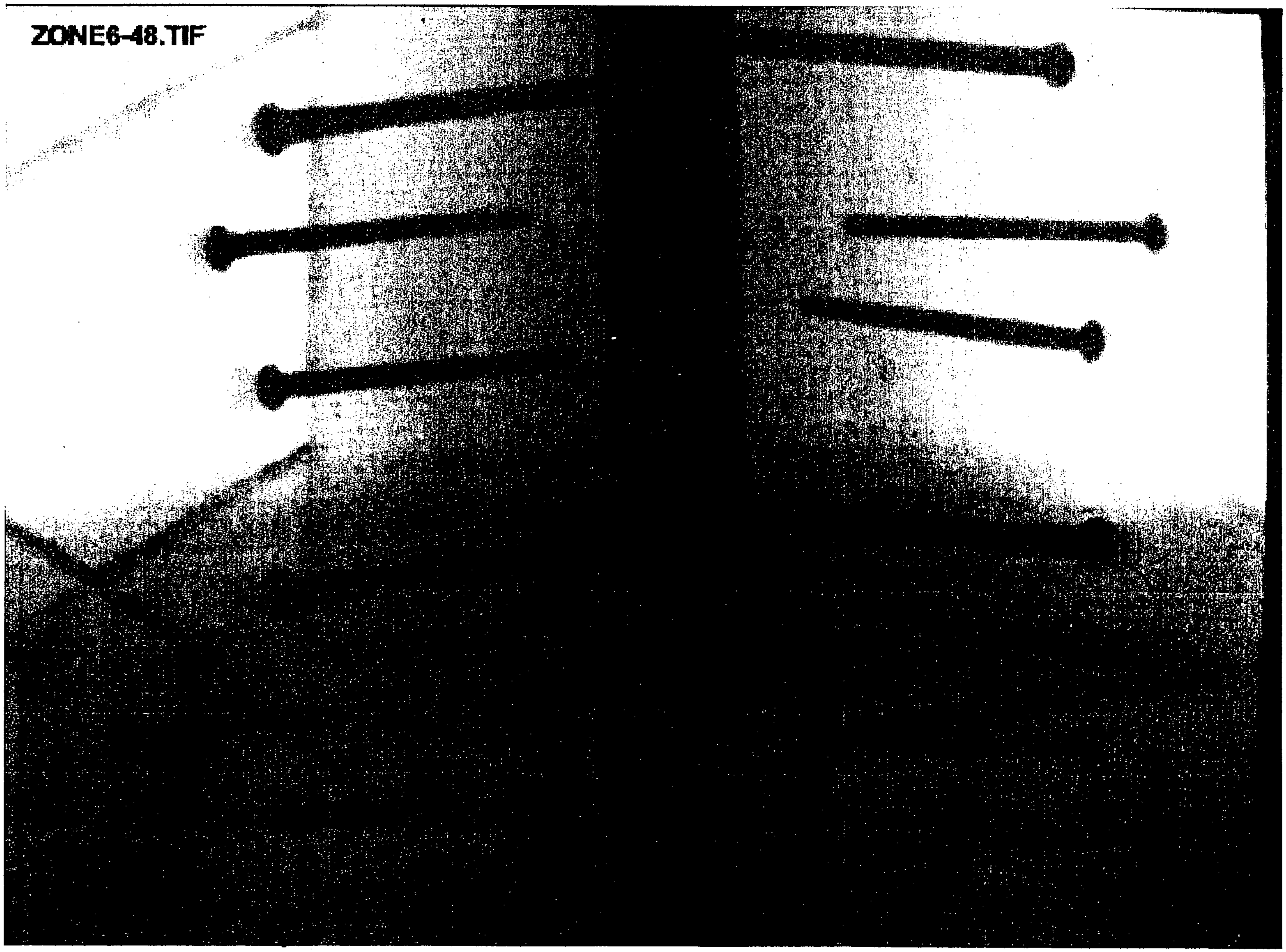


FIGURE 53 . .Real Time shot of stem at 48 inches from deck

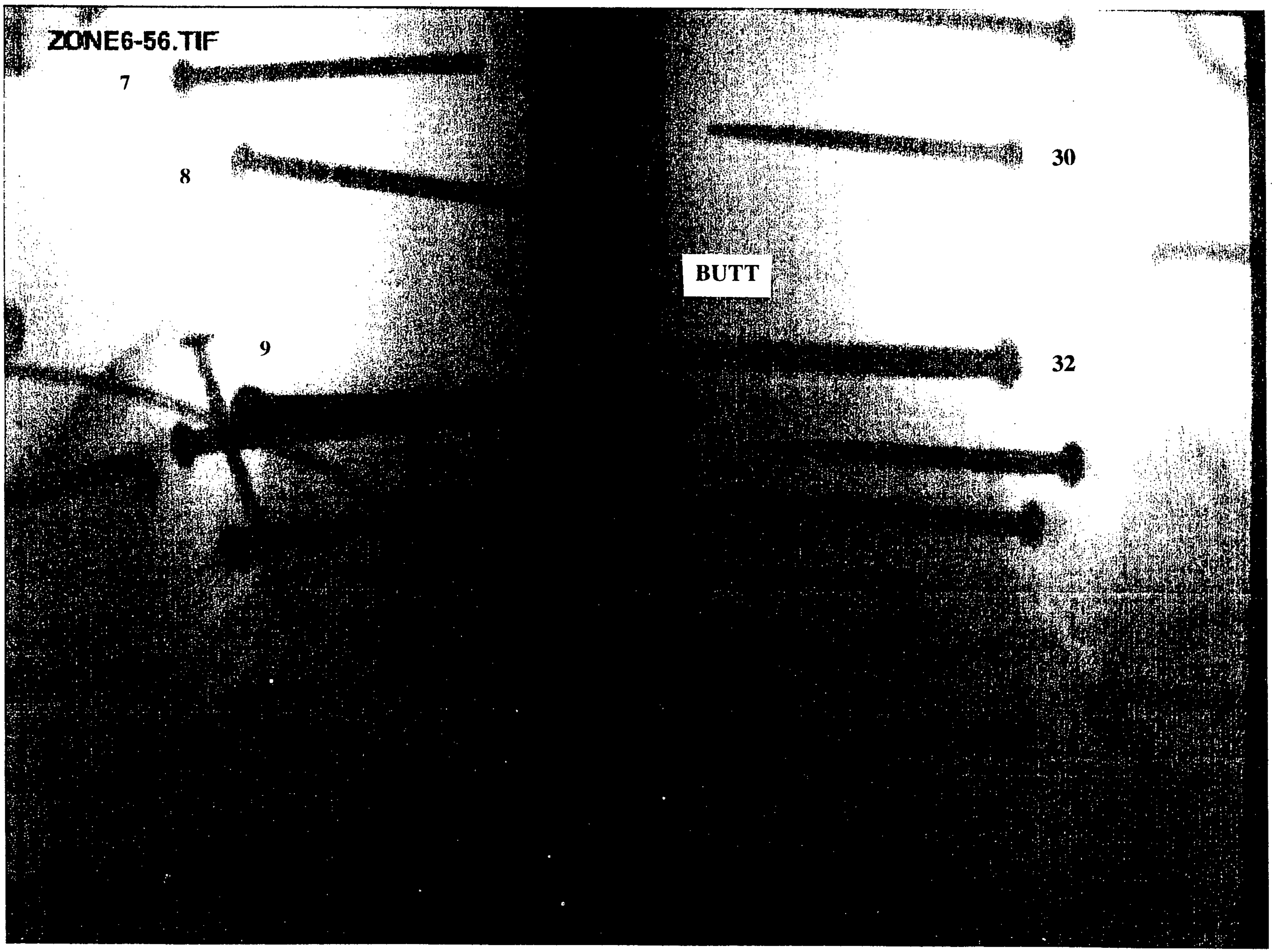


FIGURE 54 . Real Time shot of stem at 56 inches from deck

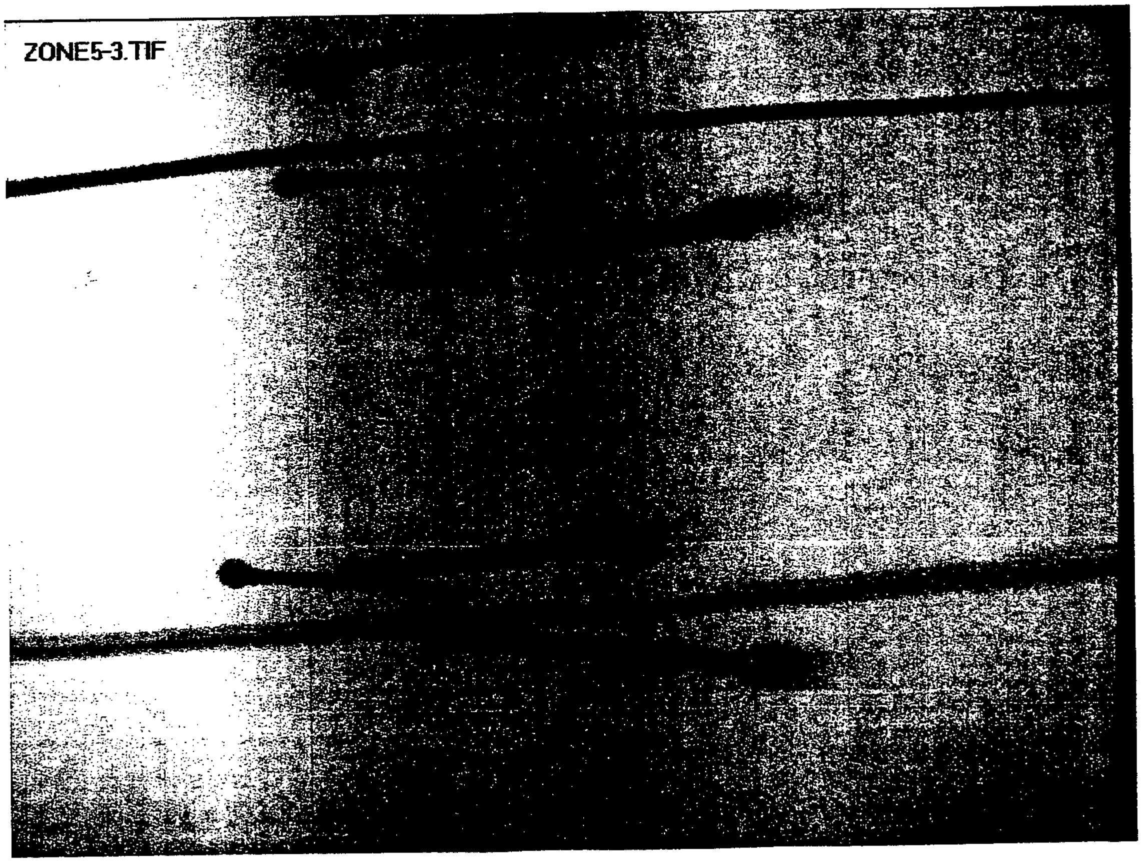


FIGURE 55. Real Time shot of Area 5

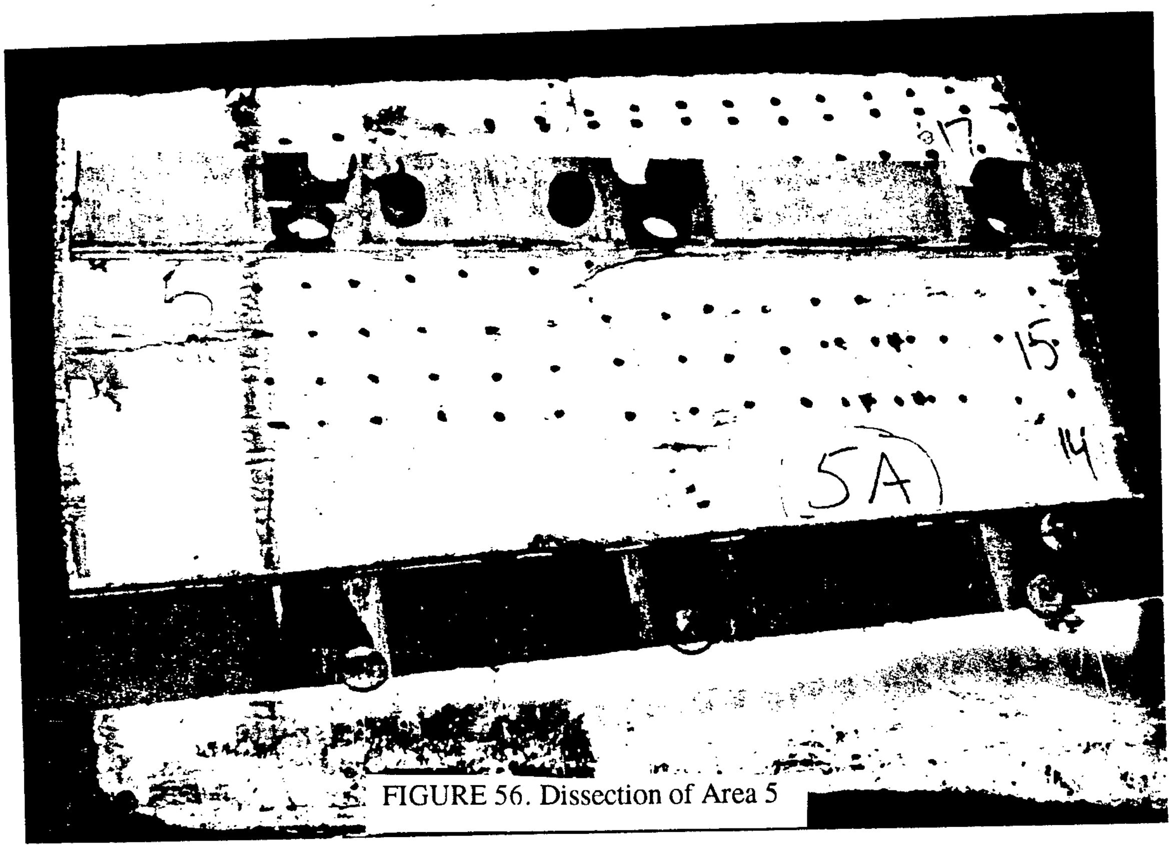


FIGURE 56. Dissection of Area 5

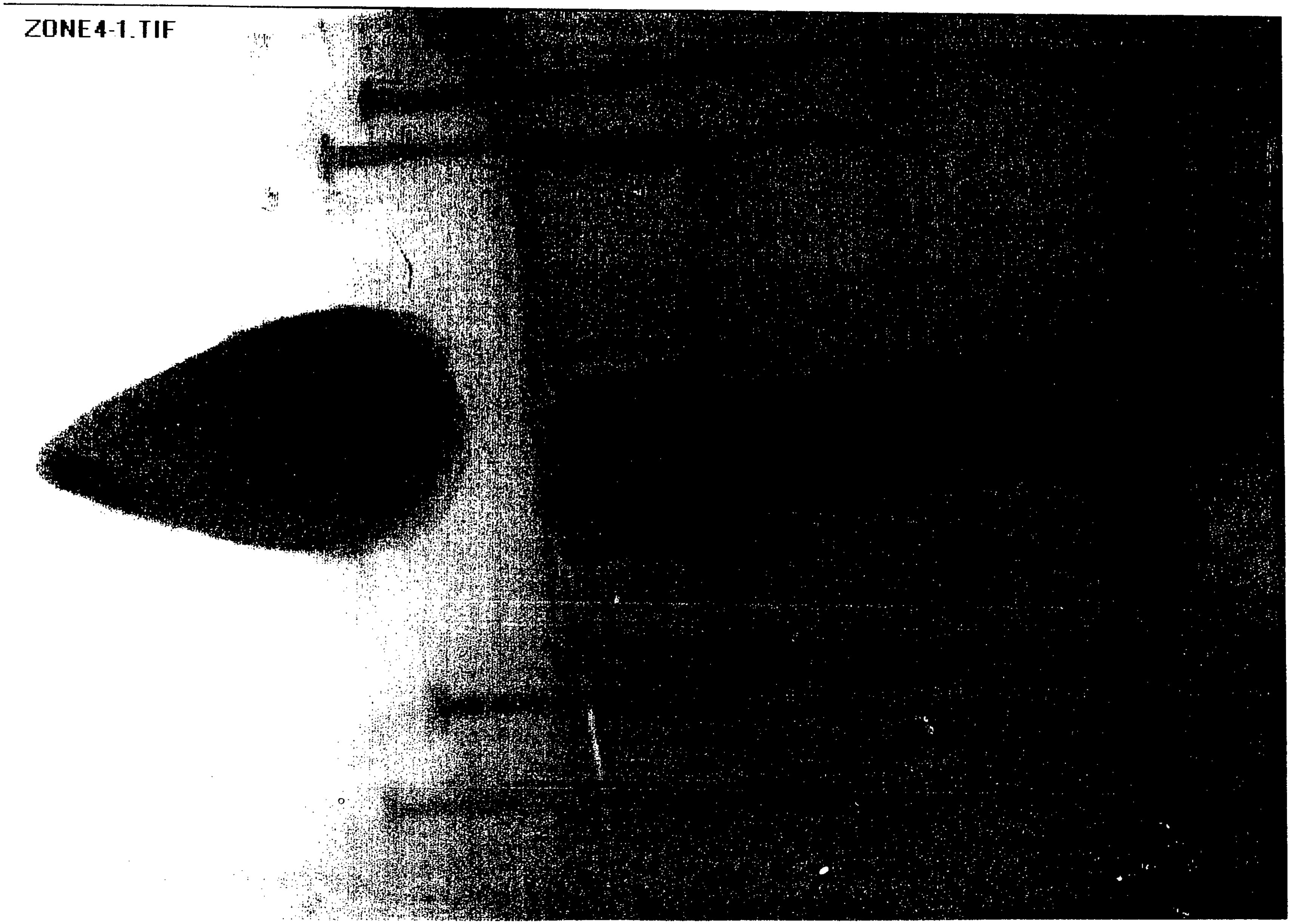


FIGURE 57. Real Time X-ray of aft keel

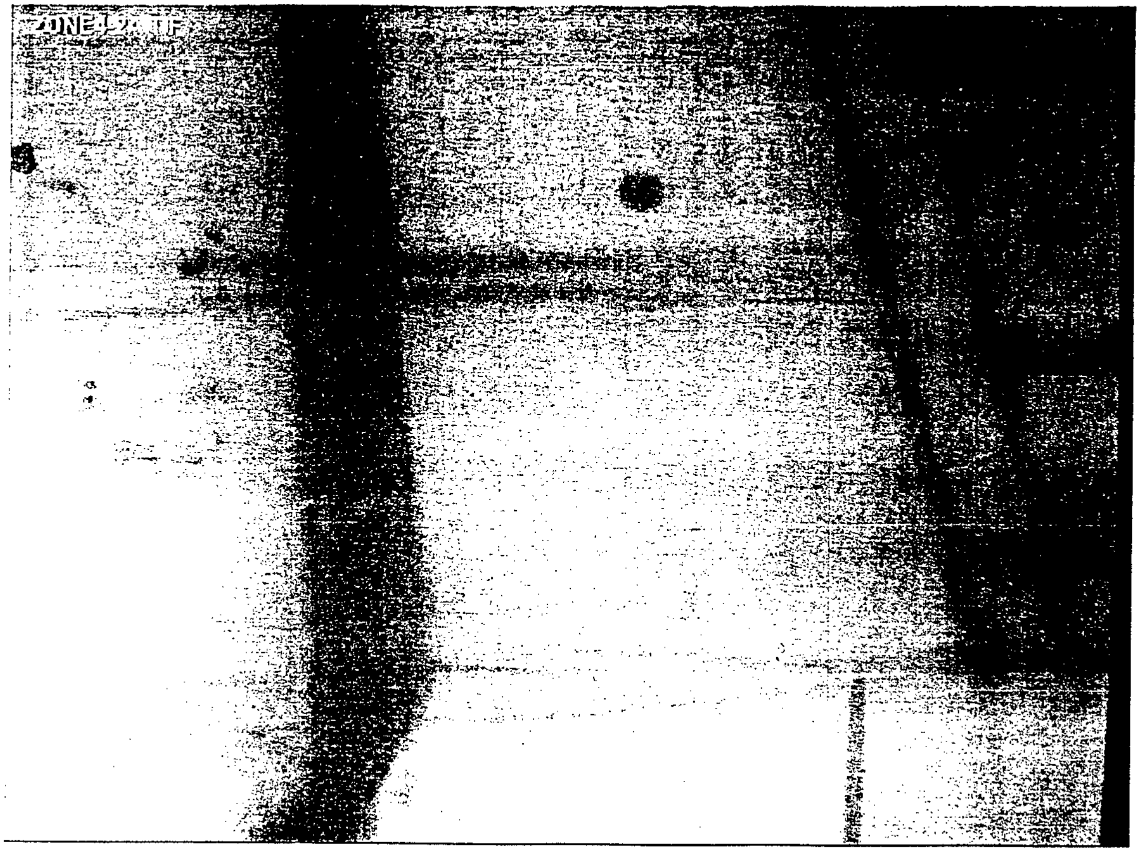


FIGURE 58. Real Time X-ray of keel bolt

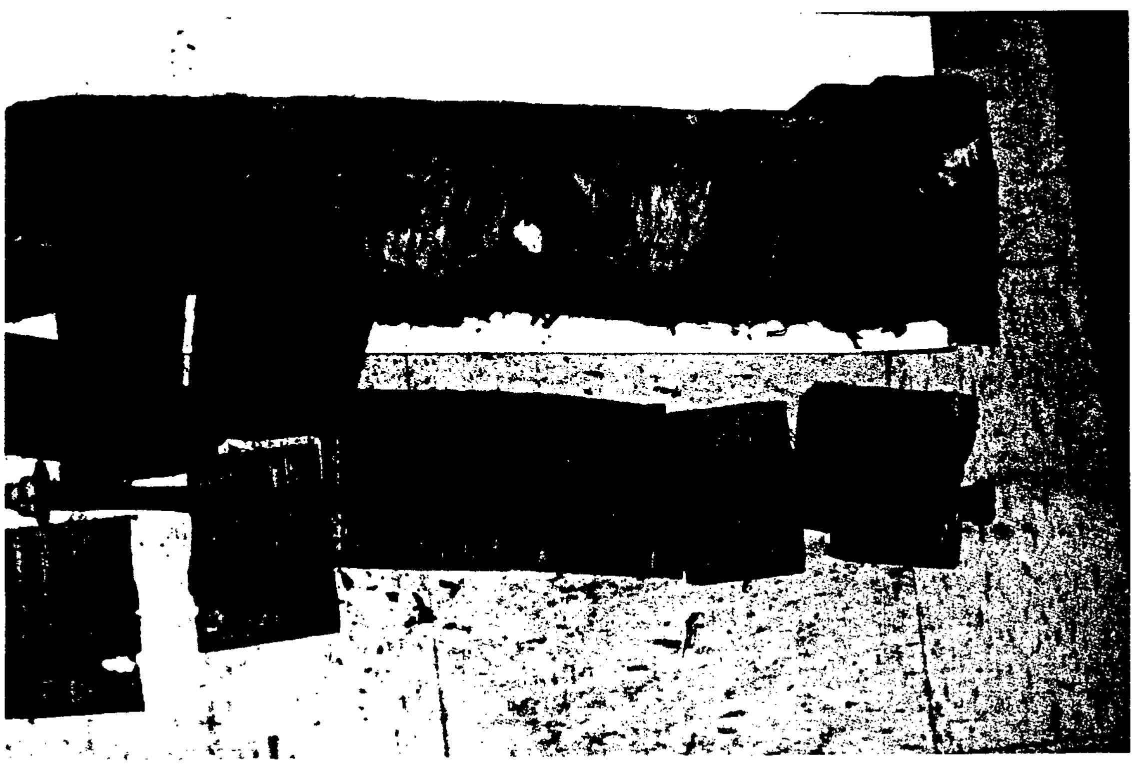


FIGURE 59. Photograph of keel bolt after dissection

FIGURE 60. Conventional X-ray of Area 2 (#1)

FIGURE 61. Conventional X-ray of Area 2 (#2)

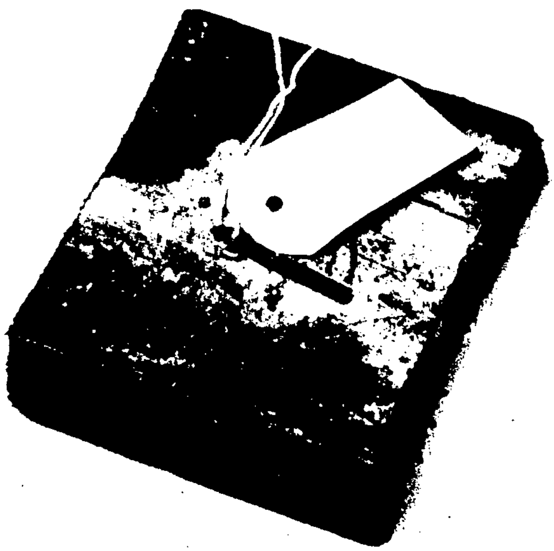


FIGURE 62. Fastener #11 and wood from Area 2

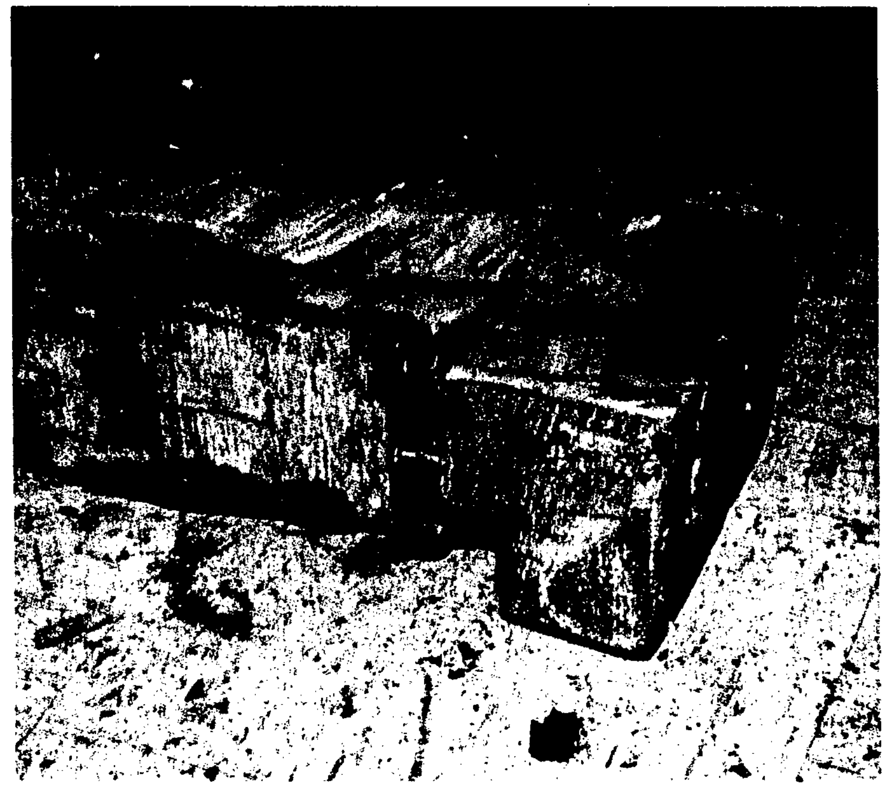


FIGURE 63. Keel piece for laboratory shots

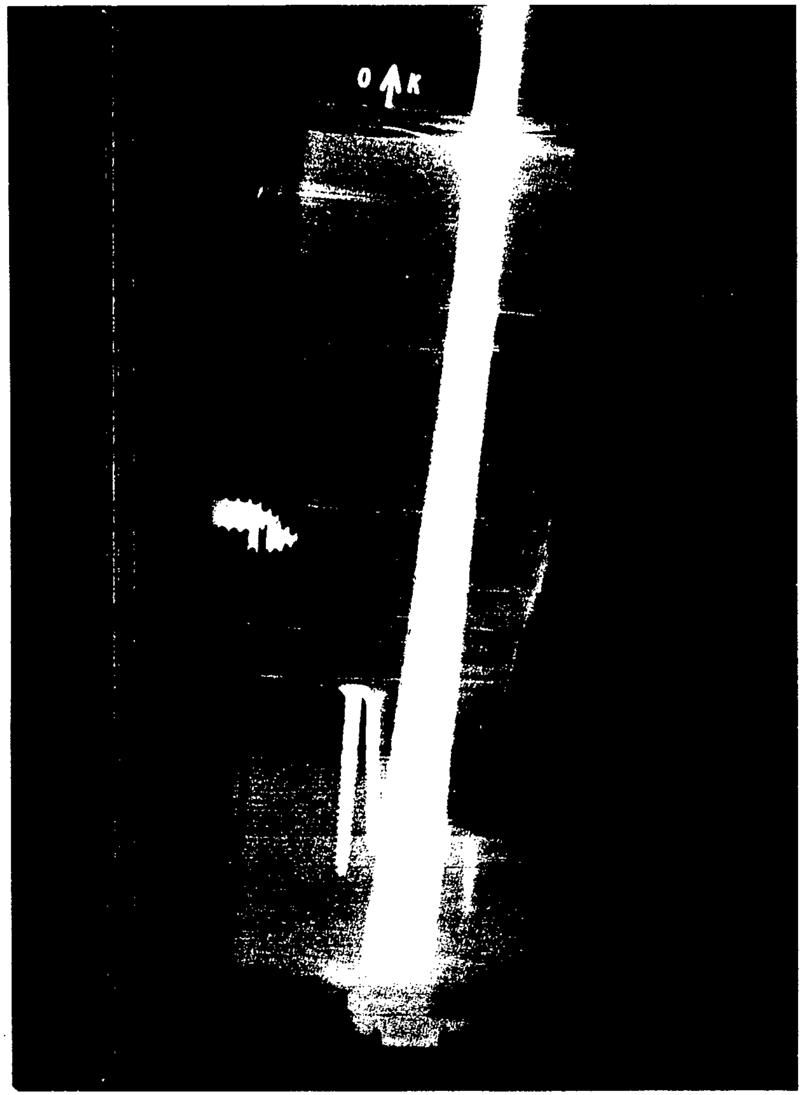


FIGURE 64. Conventional X-ray of Keel Piece at 0 degrees


FIGURE 65. Real Time X-ray of Keel Piece at 0 degrees

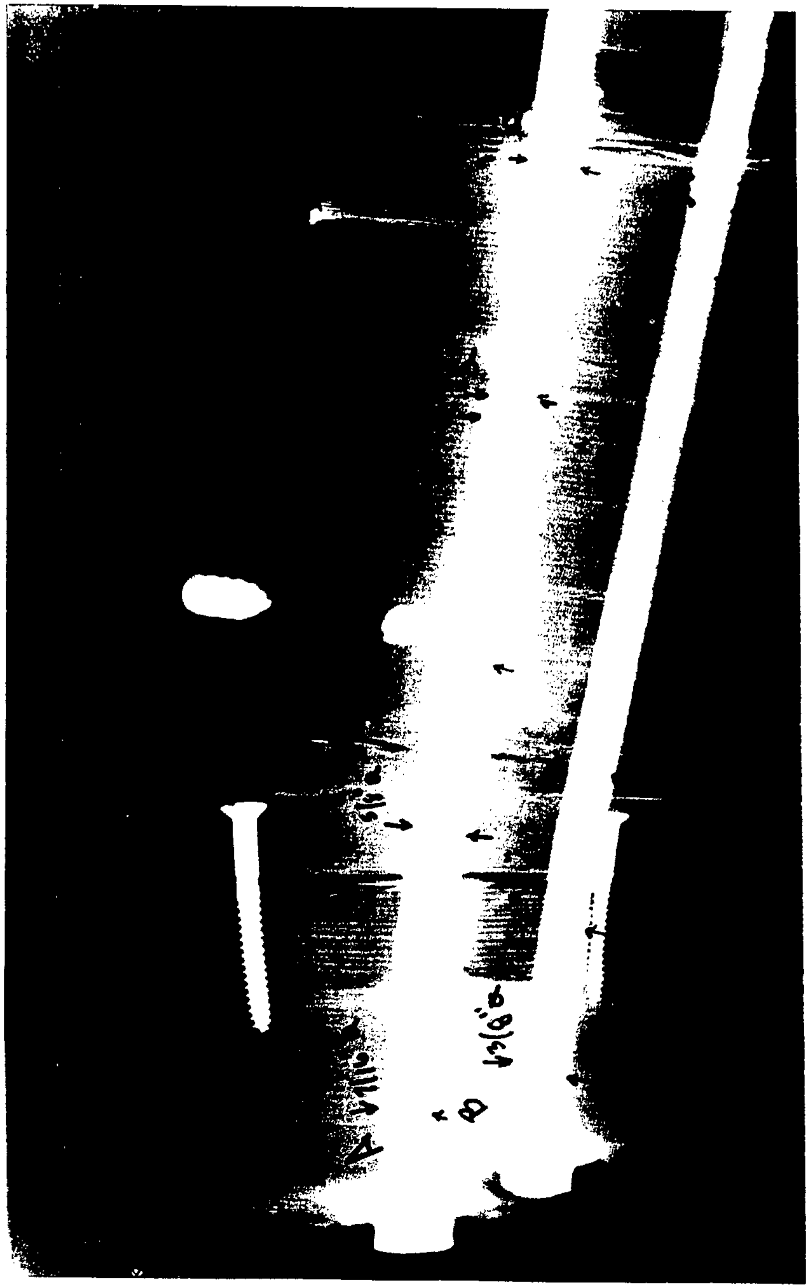


FIGURE 66. Conventional X-ray of Keel Piece at 30 degrees

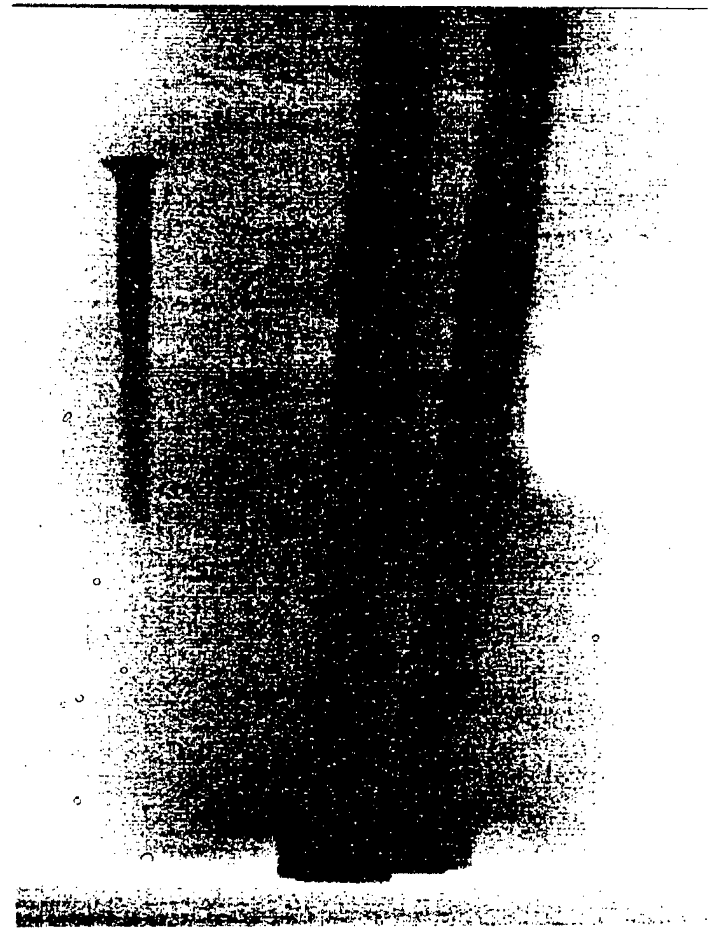


FIGURE 67. Real Time x-ray of Keel Piece at 30 degrees

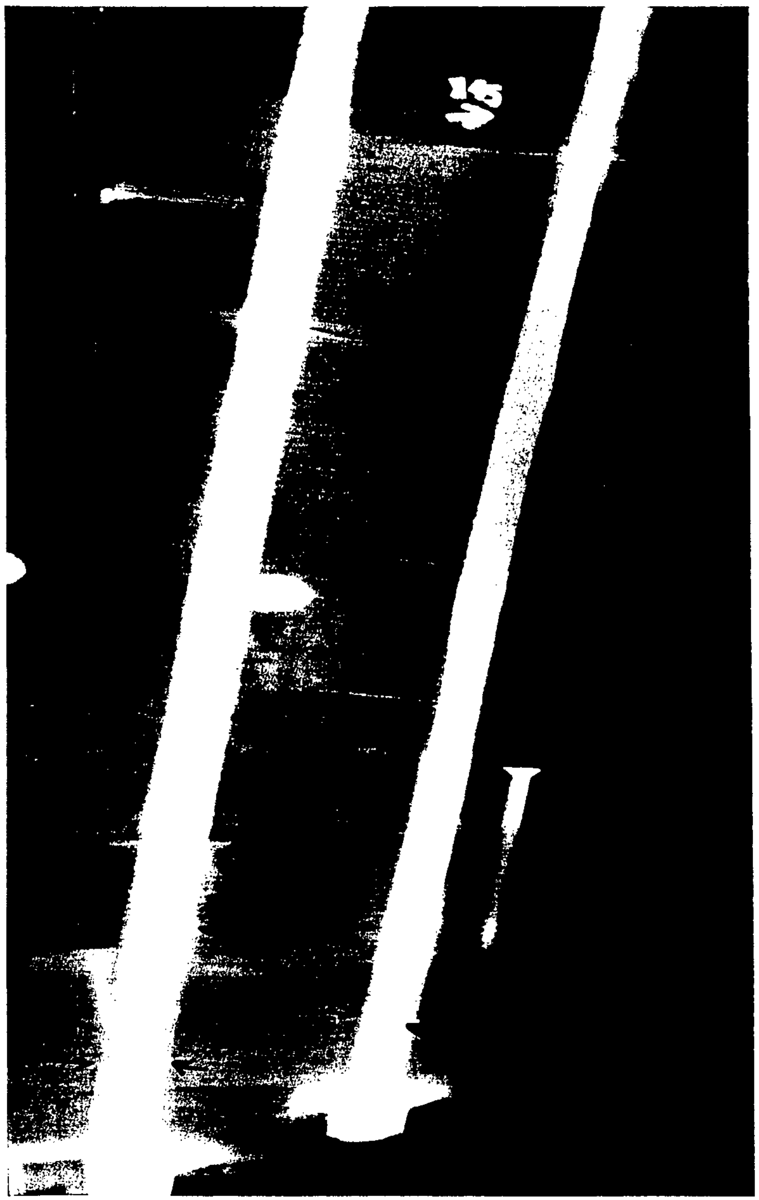


FIGURE 68. Conventional X-ray of Keel Piece at 45 Degrees

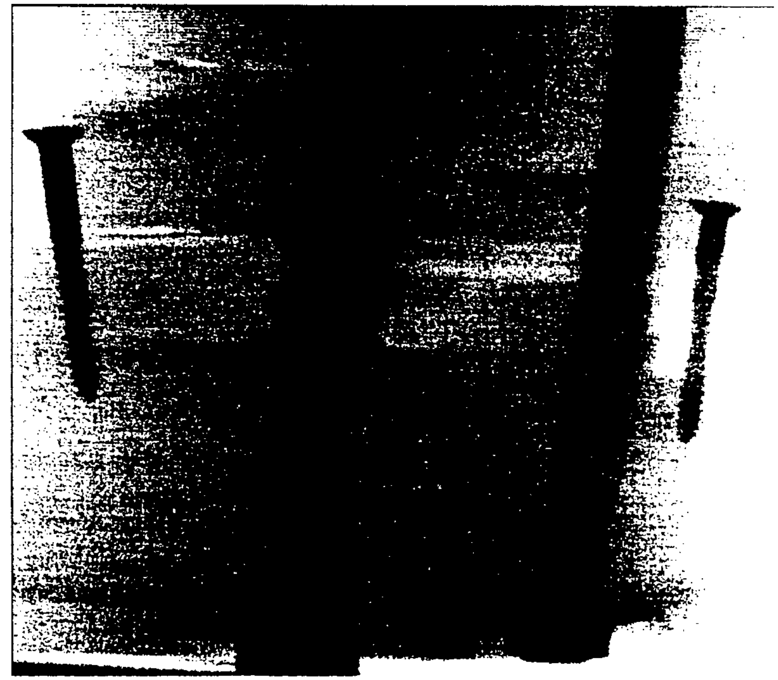


FIGURE 69. Real Time x-ray at of Keel Piece 45 degrees

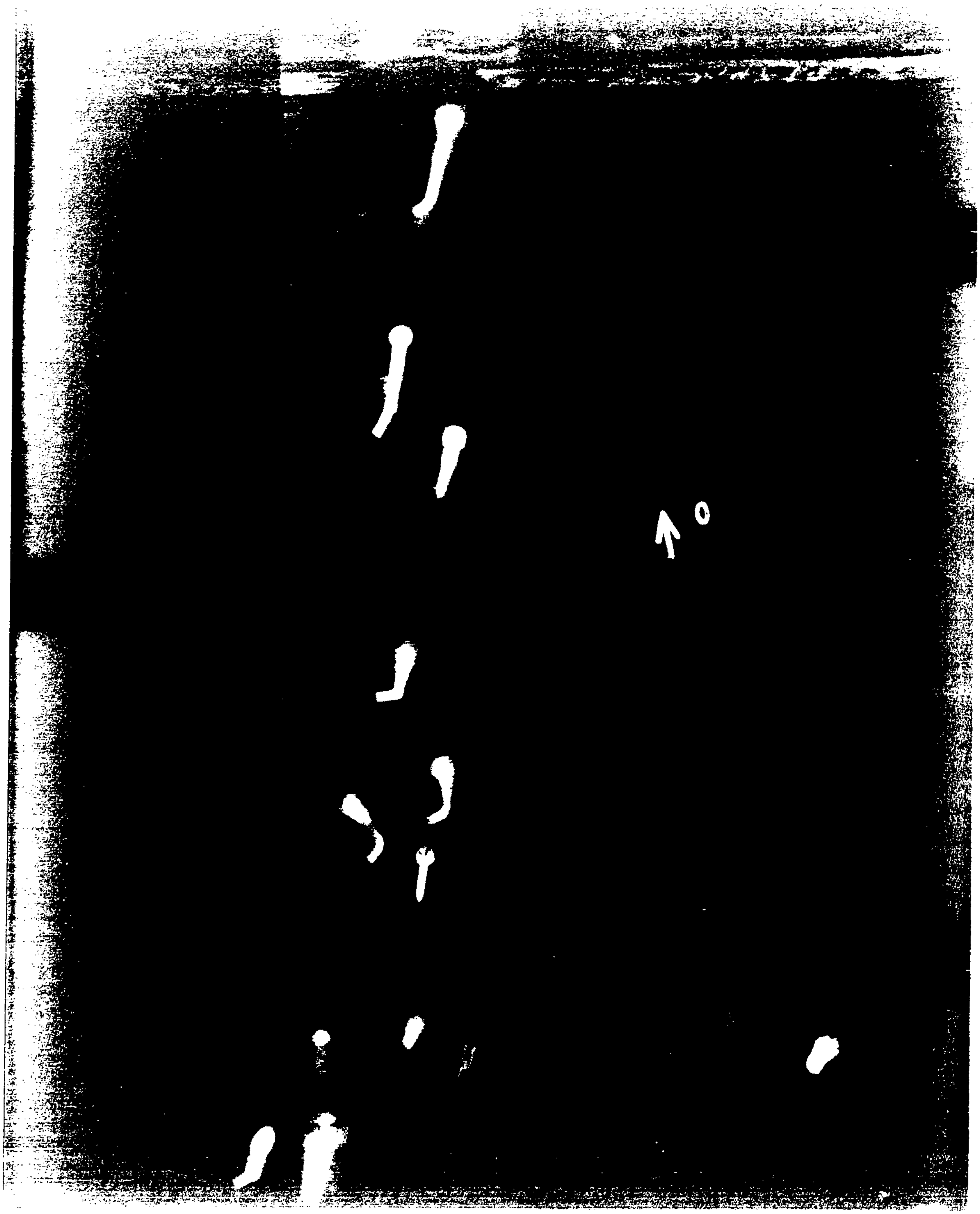


FIGURE 70. Conventional X-ray of Plank (taken from 20 degrees below)

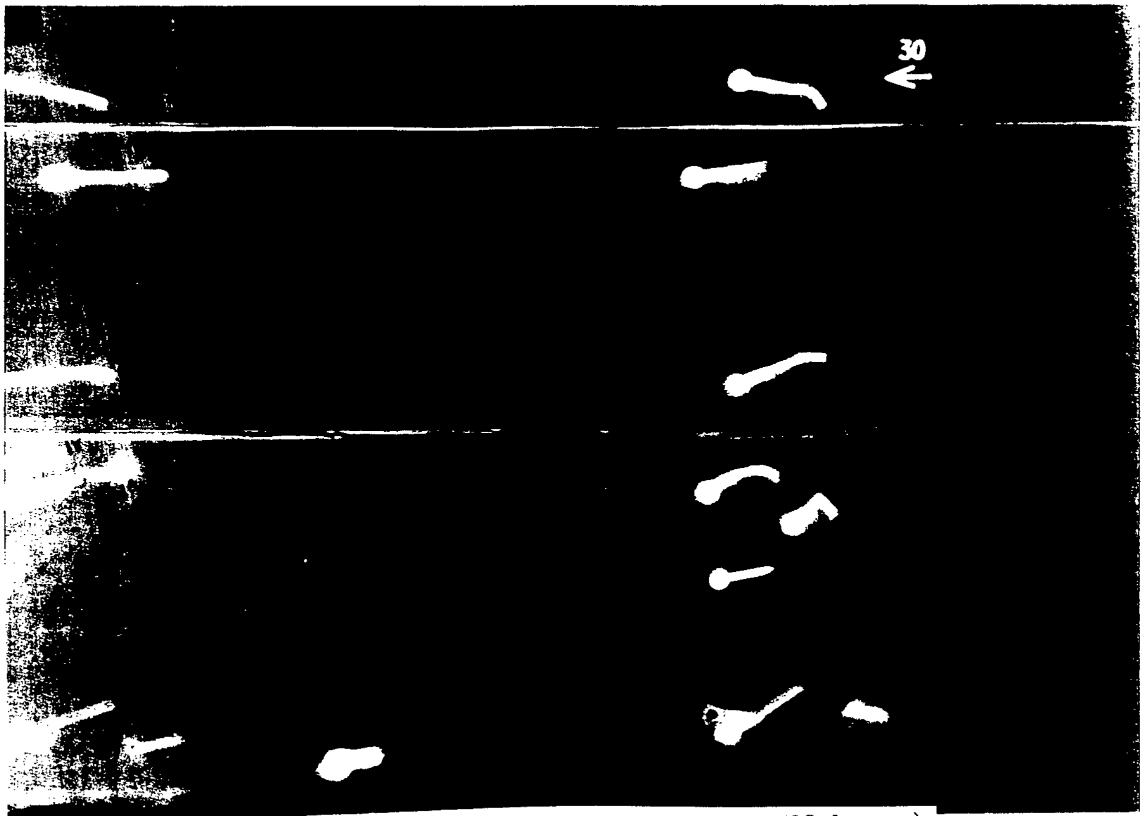


FIGURE 71. Conventional X-ray of Plank (30 degrees)

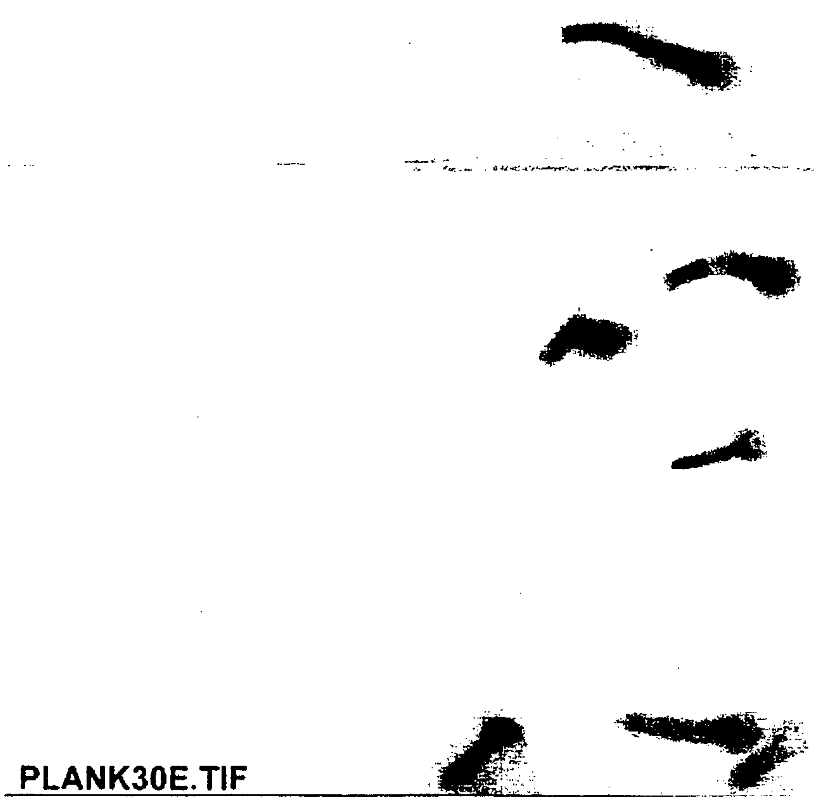


FIGURE 72. Real Time X-ray of Plank (30 degrees)

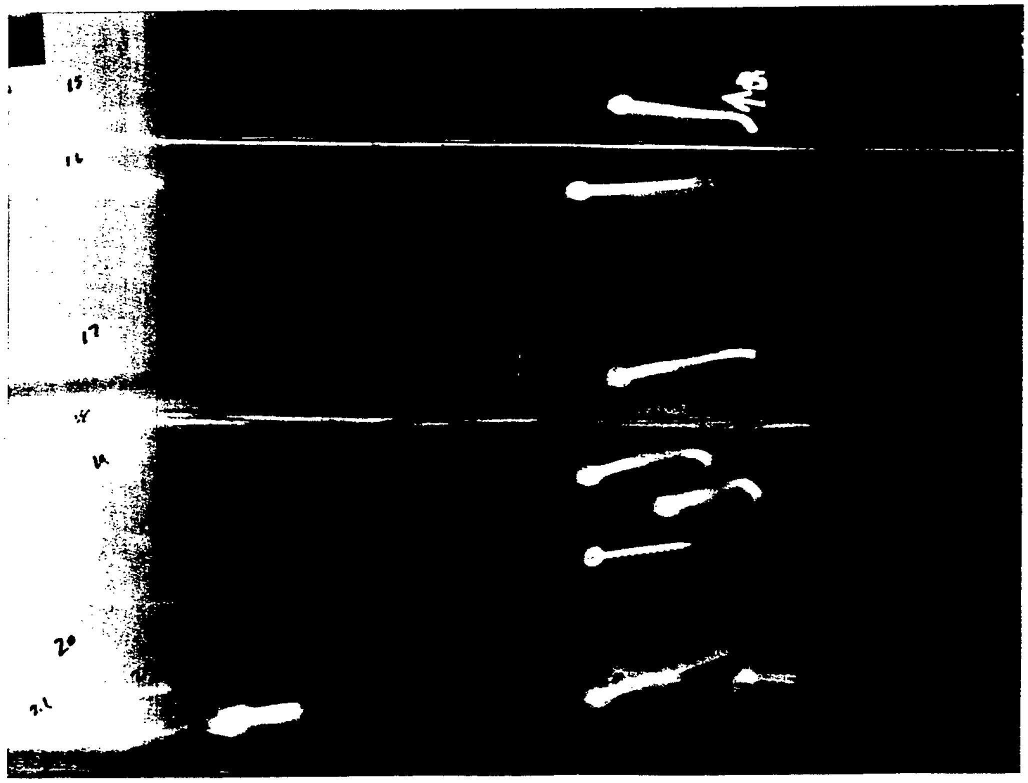


FIGURE 73. Conventional X-ray of Plank (45 degrees, ASA80)

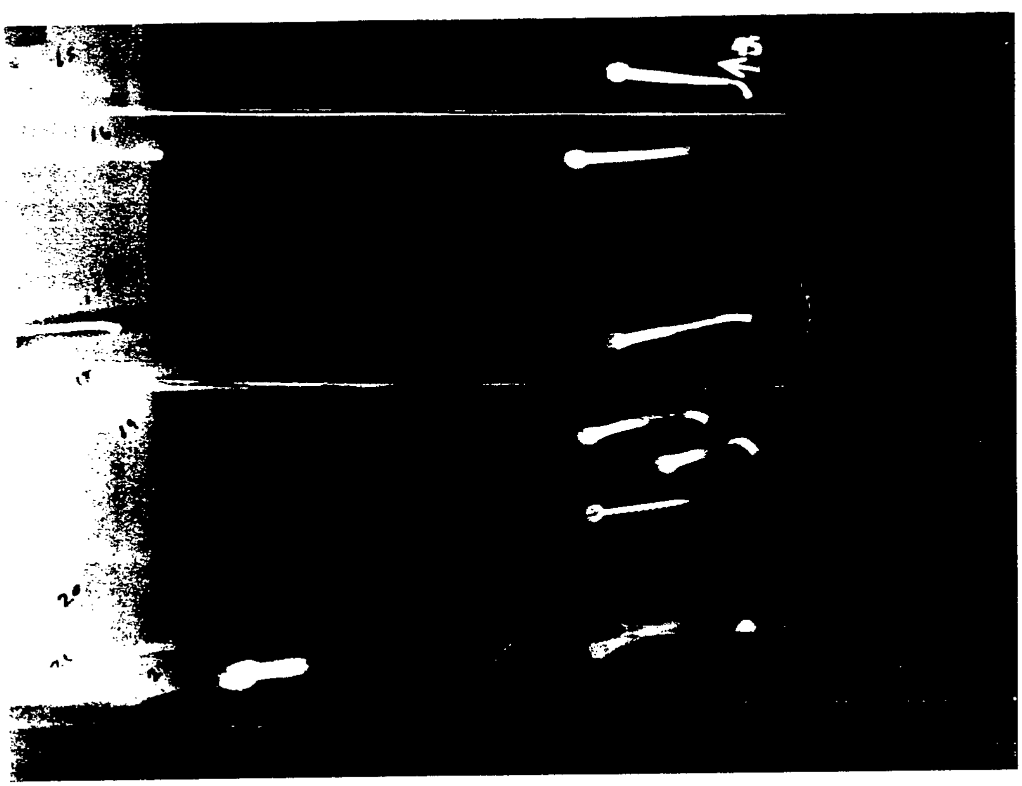


FIGURE 74. Conventional X-ray of Plank (45 degrees, ASA100)

FIGURE 75. Real Time X-ray of Planks (45 degrees)

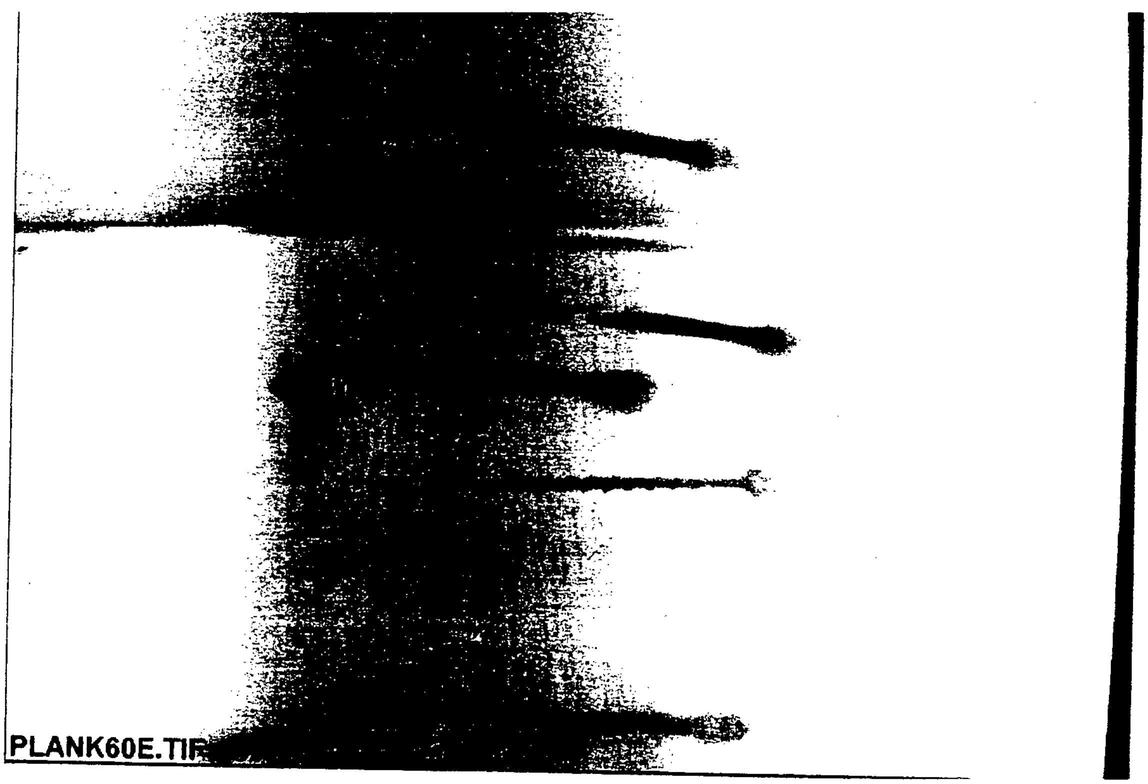


FIGURE 76. Real Time X-ray of Planks (60 degrees)

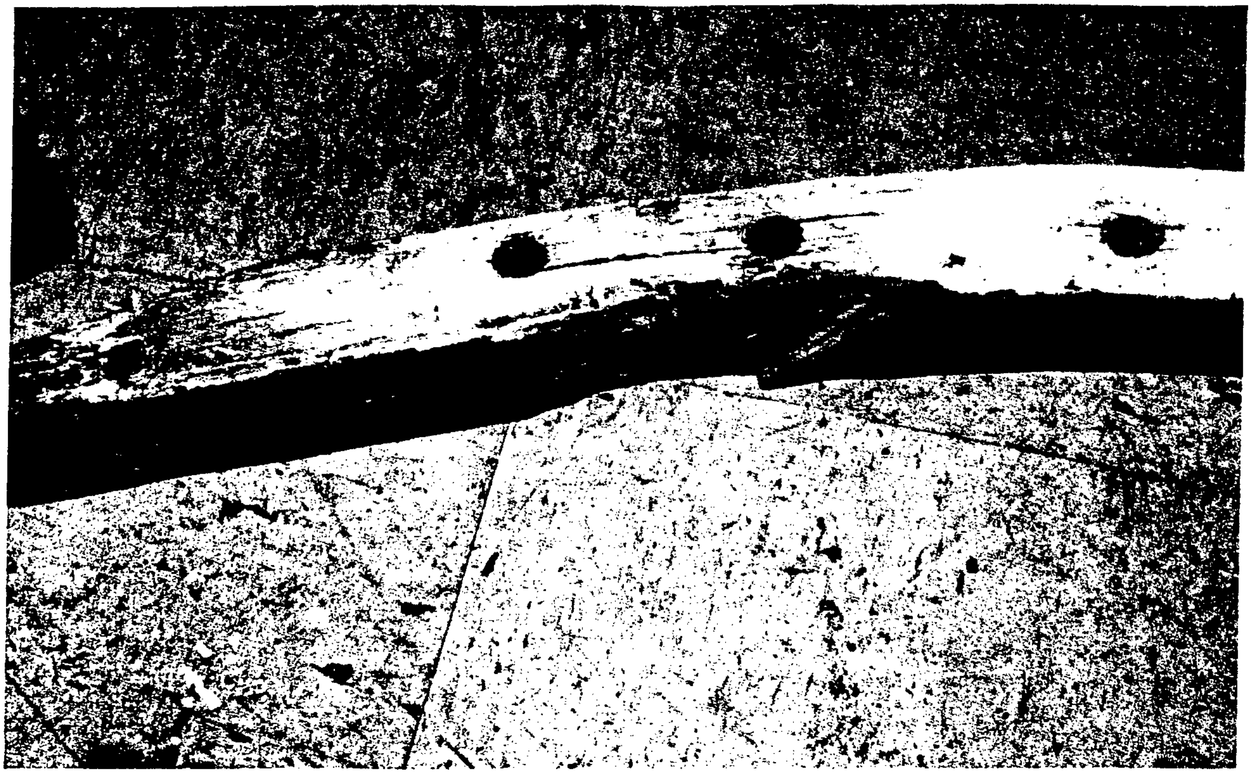


FIGURE 77. Photograph of Frame Side

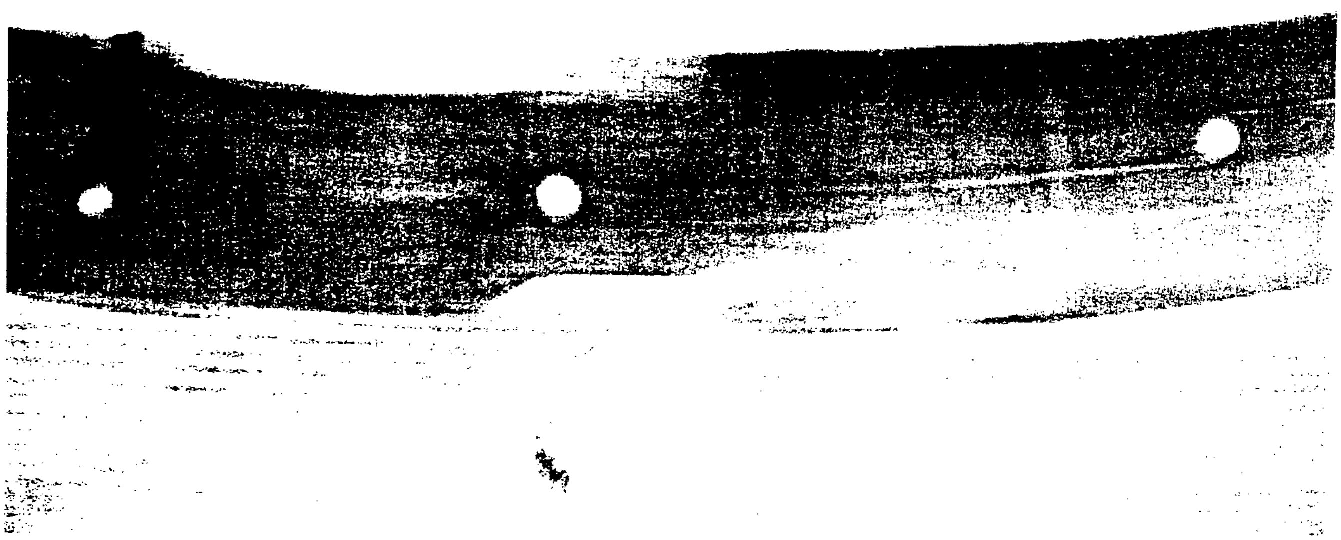


FIGURE 78. Real Time X-ray of Frame Side

FIGURE 79. Photograph of Frame Edge

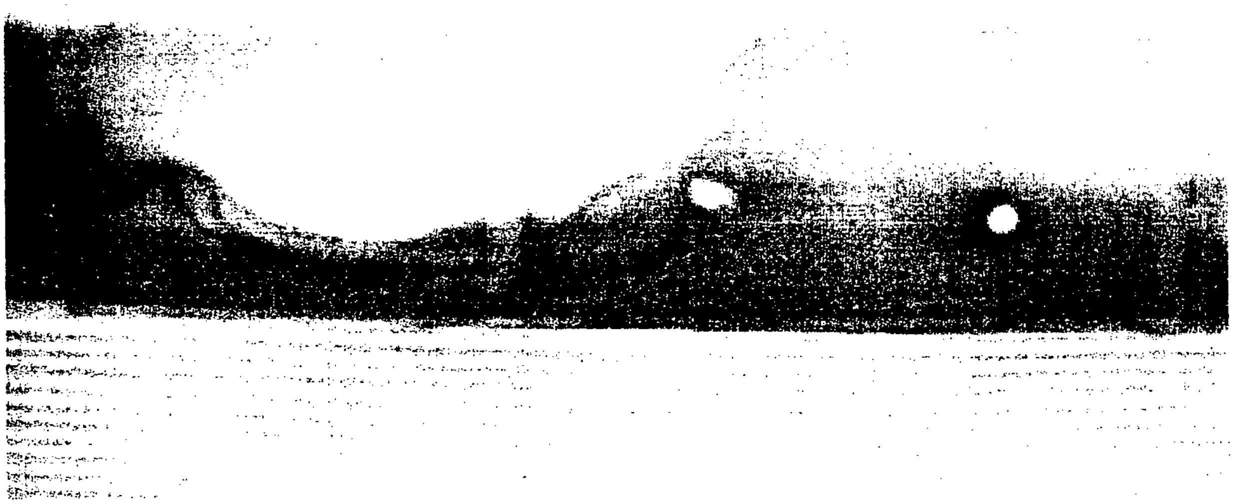


FIGURE 80. Real Time X-ray of Frame Edge

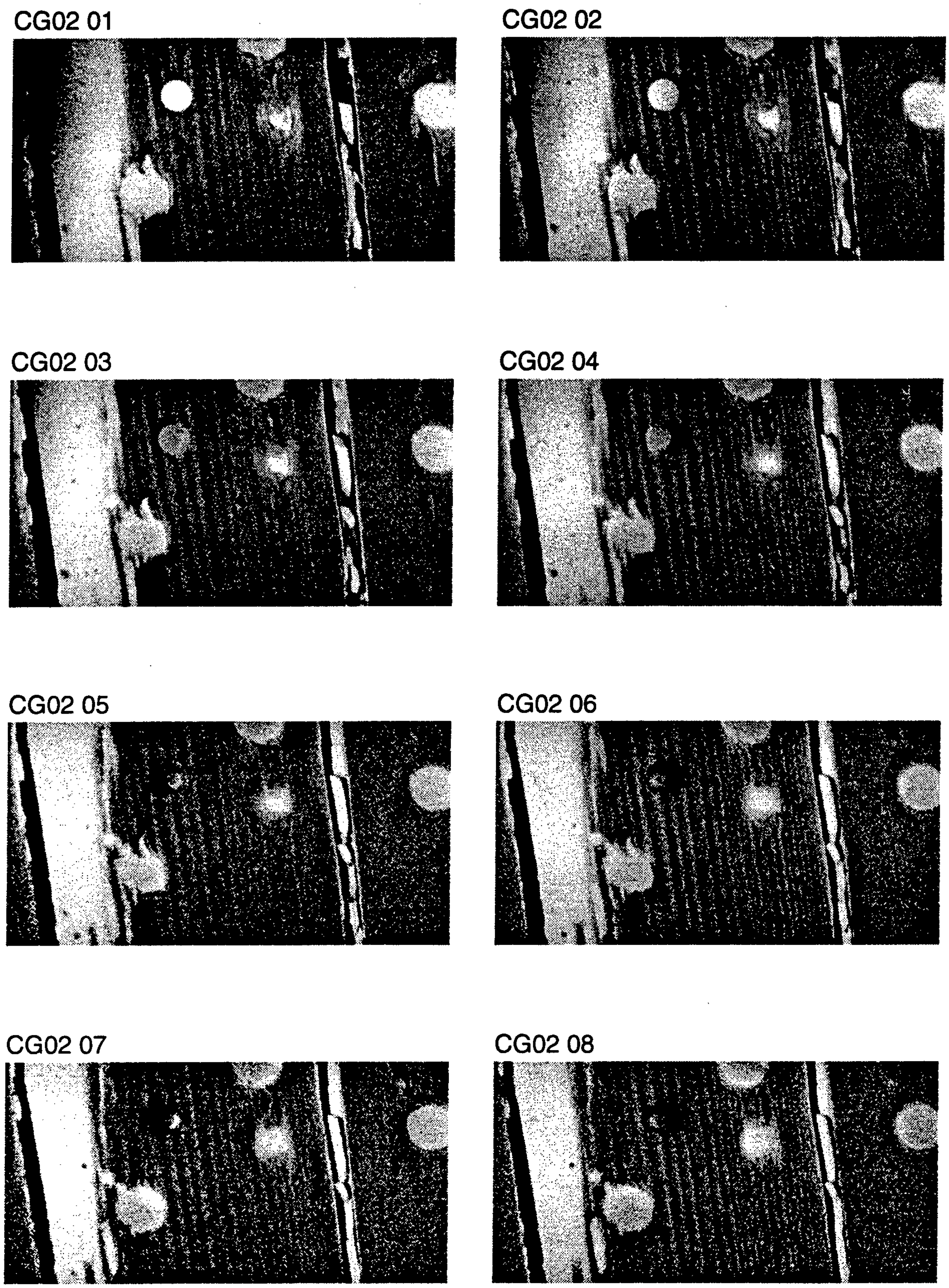
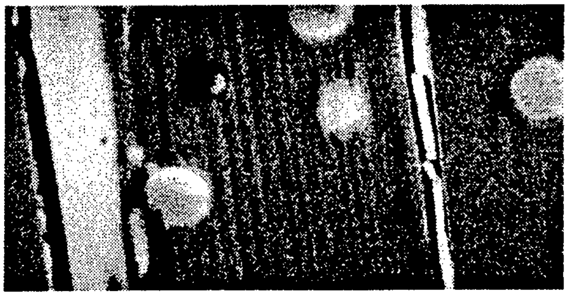
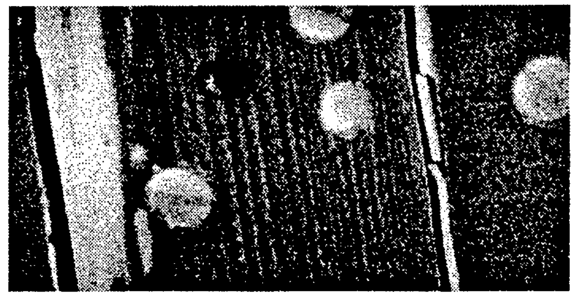


FIGURE 81. Backscatter X-ray Results

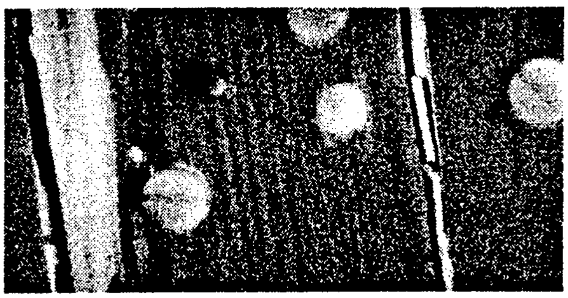
CG02 09



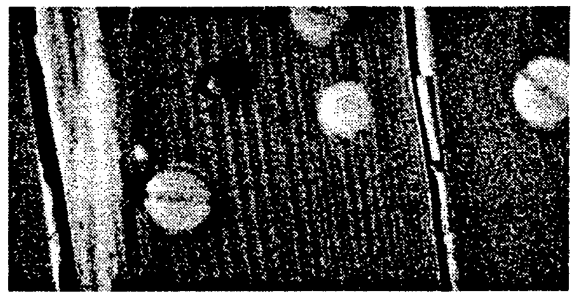
CG02 10



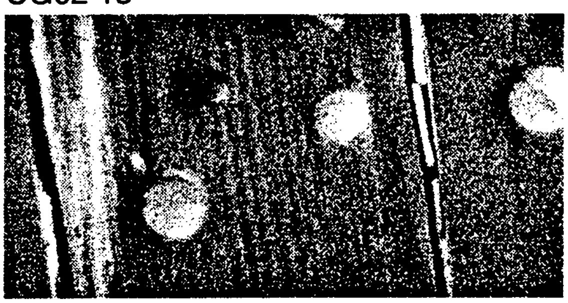
CG02 11



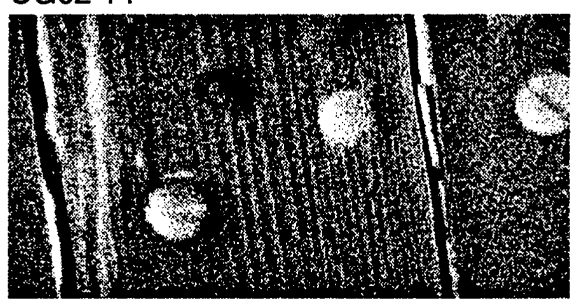
CG02 12



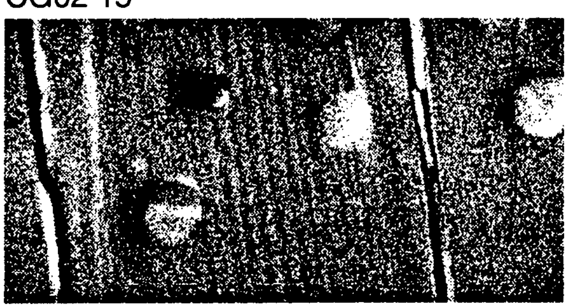
CG02 13



CG02 14



CG02 15



CG02 16

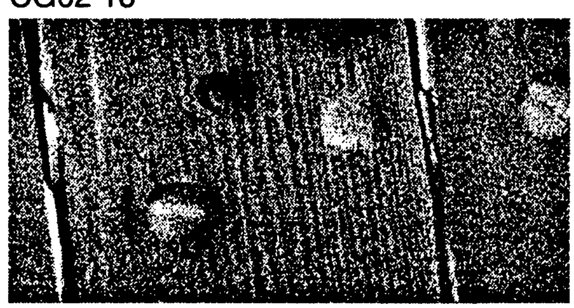
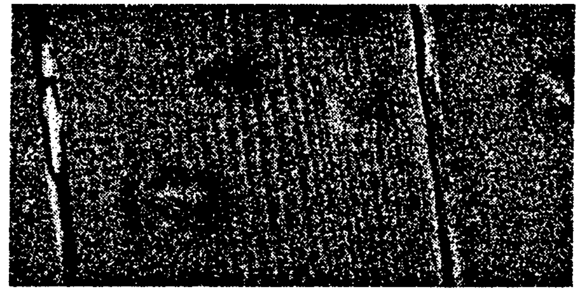


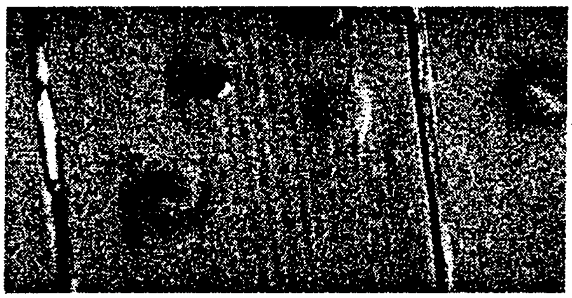
FIGURE 81. (Continued)

CG02 17

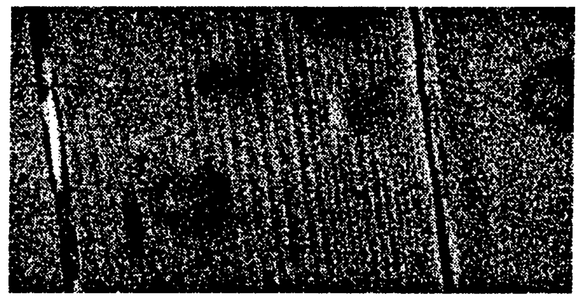
CG02 18



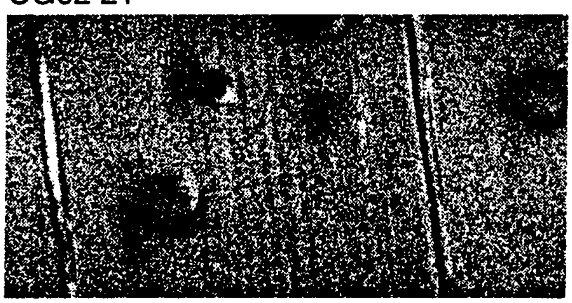
CG02 19



CG02 20



CG02 21



CG02 22

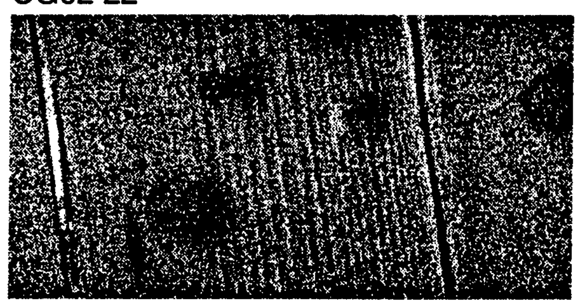


FIGURE 81. (Continued)

TABLE 1. WOODEN VESSEL TEST SCHEDULE, 9/30/96

SEPTEMBER 30	- T. Greaves, Marine Surveyor
OCTOBER 1	- LT E Christensen and CDR M. Cruder, USCG HQ - B. Pfund, Marine Surveyor, trip hammer mechanism - J. Klopman, marine surveyor
OCTOBER 2	- Talk at RDC at 2:00 by Dr. R. Ross, Forest Products Laboratory
OCTOBER 3	- Dr. R. Ross, equipment demonstration
OCTOBER 8	- Integrated Technologies, Inc., standard x-ray - SAIC, real-time x-ray - ANVIL Corp., consultants (performed previously done vessel x-ray) - Engineering Data Management, Inc., consultant; also with Resistograph.
OCTOBER 17-18	- Computer Application Systems, Inc., "CAPACIFLECTOR" - R. Faris, marine surveyor and ultrasonic NDE of bolts

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Guidance on Inspection, Repair, and Maintenance of Wooden Hulls

ENCLOSURE (1) TO NVIC 7-95
COMPILED BY THE JOINT INDUSTRY/COAST GUARD
WOODEN BOAT INSPECTION WORKING GROUP
October 1995

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J. CREVICE CORROSION

Stainless steels are subject to a particular type of corrosion called crevice corrosion, which is a severe form of pitting. Crevice corrosion can destroy a fastening in a few years while only damaging a small fraction of the total mass of the fastening. The austenitic stainless steels (including the most commonly encountered types, 304 and 316) derive their corrosion resistance from a surface oxide film which is self-repairing in air or in the presence of oxygen dissolved in an electrolyte. In stagnant areas like wet wood or underneath marine growth or paint, however, oxygen can be depleted by cathodic activity, allowing the ever-present chloride ions to destroy the film in small areas, which then undergo unpredictable and exceedingly rapid corrosion. Unfortunately, wet wood is a nearly perfect environment for crevice corrosion. Stainless steel must be used with great caution as a fastening material for wooden boats, and inspectors should be suspicious of all stainless steel fastenings, especially wood screws, used on boats in saltwater service. Type 316 contains more nickel and chromium than type 304, and it also contains molybdenum, which inhibits crevice corrosion to a certain extent, but it is not completely immune. Barbed or "ring" nails of type 316 are available, but wood screws of type 316 are generally not available.

K. INSPECTION OF FASTENINGS

A boat is no better than its fastenings. The most common type of fastenings found on wooden boats are screws, however, certain types of construction utilize nails, bolts or rivets. Most hull fastenings are concealed from view, being countersunk and covered; therefore their inspection is difficult.

Regardless of the type of fastenings involved, inspection to ascertain condition is necessary in most plank on frame boats.

For purposes of uniformity careful fastening inspection must be carried out on all vessels. Removal of fastenings should be conducted as follows:

1. For Cause - Saltwater And Freshwater Service Remove fastenings whenever inspection reveals the probability of defects such as when a plank or planks are "proud" and have moved away from the frames or indications of loose bungs, rust bleeding from fastening holes etc., are noted.

   Particular attention should be given to exposed hull fittings and through bolts accessible inside the hull, such as keel bolts, chine bolts, and double frame, clamp, and floor timber bolts. These are as important to the total hull structure as plank fastenings. They should be sounded with a hammer or wrench tightened and, if suspect, some should be pulled for inspection. Often a bolt will be completely wasted away in the middle, at the faying surface of the joint, and will break and come out when pried up. This is caused by moisture accumulation which, besides wasting the fastenings, forms an excellent place for wood decay to start.

2. <u>Periodic</u>. Inspection of fastenings can prevent planking/frame failure. Random sampling of fasteners should be part of a regular maintenance program for continuously monitoring the structural condition of the vessel. Therefore for vessels designed and built to Subchapter "T" Inspection Standards, random sampling of fastenings should begin at the 10th year of age and every 5th year thereafter in **salt water service** and 20th year of age and every 10th year thereafter in **fresh water service**.

For existing vessels not originally built to Subchapter "T" Inspection Standards but certificated later in life, random sampling should begin at the 5th year of age and every 5th year thereafter in **salt water service**, and 10th year of age and every 10th year thereafter in **fresh water service.**

Scope Of Periodic Random Sampling Of Fastenings.

a. Remove a minimum of eight fastenings per side below the waterline.

b. Concentrate sampling in the following areas:
   - Garboard seams
   - Stem joints
   - Plank ends in areas of bent planks
   - Shaft log(s)
   - Under engine beds where vibration is maximum

c. In vessels of cross plank (CHESAPEAKE BAY DEADRISE) construction, specifically inspect fastenings at the keel and chine joints, at transom attachments, and over the propeller(s).

It is extremely important that the type, material, and location of the fastenings removed, along with a description of their condition be accurately documented. This includes areas of the vessel which have undergone refastening as well. Use of a camera is invaluable in recording areas of interest during inspections.

Composite, cold molded and laminar built-up wooden hulls often depend on adhesives and resins for fastening purposes. Inspection of these type vessels requires common sense and good judgement to identify the method of construction used and thereby determine the extent of inspection required. Generally, these vessels do not require periodic random sampling of fastenings by removal except for cause.

APPENDIX A-3

E. MECHANICAL FASTENINGS; MATERIALS

Mechanical fastenings should be of material suitable for the service intended. Ferrous fastenings should be hot-dipped galvanized. Among the usual non-ferrous types brass is not acceptable in salt water applications as it will corrode from de-zincification and is inherently soft and weak.

Caution should be used in selecting fastening material because of the problem of galvanic action which can arise if dissimilar metals are used close to one another. A bronze washer used with a steel bolt will result in the eating away of the steel. Proper selection of fastening materials will significantly prevent corrosion and thereby extend their service life.

Marine applications of stainless steel alloys (chromium-nickel) are subject to a phenomenon known as contact corrosion or more commonly, crevice corrosion. Stainless steels which are in contact with each other or placed in tight joints (nuts and bolts), swage connections (standing rigging), or used to fasten wood planking below the waterline, corrode at an alarming rate. The vehicle of crevice corrosion is electrolytic cell formation. If the stainless steel is unable to naturally form a thin film of chromium oxide to shield the material from attack, corrosive liquids such as salt water are able to establish electrolytic cells with chloride ions and corrosion takes place. In short, stainless steel depends on oxygen to provide protection against crevice corrosion.

Grade 316 L (passive) stainless steel is the most accepted material for marine applications due to the introduction of molybdenum to the alloy. For example: grade 304 stainless steel has 18% chromium and 8% nickel in the alloy while grade 316 L has 18% chromium and 10% nickel and 3% molybdenum. Grade 304 is quite susceptible to crevice corrosion when employed in tight spaces and unable to generate chromium oxide. The 316 L material will last longer in the same application.

Chandlers usually stock only brass and stainless steel, both being very unsuitable for underwater fastenings. The grade of stainless is rarely mentioned and is often only Type 304.

Generally, stainless steel fasteners should not be used underwater. However, they are used quite frequently, but only if all of the following conditions are met will they be satisfactory:

(a) Austenitic grade at least Type 304, preferably Type 316.
(b) Not passing through wet wood.
(c) Ample sealant under the head and in between mating surfaces.
(d) The item to be fastened is less noble than stainless; i.e. all the copper alloys and, with some risk of hole enlargement, steel and iron.

Note: Condition (b) indicates that stainless wood screws should never be used underwater.

The choice of stainless steel fasteners below the waterline should be carefully considered based on the water salinity, grade of stainless steel fastener available, and material of other fasteners and fittings in the hull. Stainless steel may be subject to varying degrees of accelerated crevice corrosion. For more information, see Metal Corrosion in Boats, (Reference 13).

The number, size, type and spacing of fastenings for various applications are given in Lloyd's Rules and Regulations for the Classification of Yachts and Small Craft, Part 2, Chapter 4.

A general guide for use of the various types of fastenings follows:

F. SCREW FASTENINGS

1. Lead Holes. Lead holes for wood screws should be about 90% of the root diameter of the screw for hardwoods and about 70% of the root diameter for softwoods. For large screws and for hardwoods, a shank hole of a diameter equal to the shank of the screw and of a depth equal to the shank may be used to facilitate driving. Lag screws should always have a shank hole.

   The lead hole for the threaded portion of a lag screw should have a diameter of 65-85% of the shank diameter in oak and 60-75% in Douglas Fir and Southern Pine with a length equal to the length of the threaded portion. Denser woods require larger lead holes and the less dense require smaller holes. For long screws or for screws of large diameter, lead holes slightly larger than those recommended here should be used. The threaded portion of the screw should be inserted by turning and not by driving with a hammer.

   Where possible, screws should be selected so that the unthreaded shank penetrates the joint for greatest strength and corrosion resistance, and to facilitate the drawing together of the members. In this case, the shank hole shall extend the full length of the shank. If conditions prevent the shank from extending through the joint, the shank hole shall extend

completely through the member containing the head, to prevent threads from engaging in that member, which might prevent the joint from drawing up.

Figure A: Typical Wood Screw

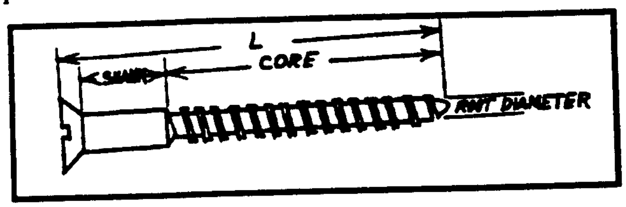
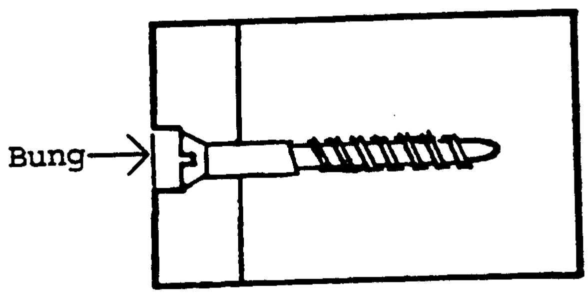


Figure B: Wood Screw Properly Inserted And Countersunk



2. Lubricants. Suitable lubricants such as wax, grease, or heavy paint, but never soap should be used on screws, especially in dense wood, to make insertion easier and prevent damage to the screw.

3. Depth. Penetration of the threaded portion for at least a distance of 7 screw diameters for hardwoods and 10-12 in softwoods is required for maximum holding power.

4. Loading. If possible, screws should be placed so that they are loaded across the screw and not in the direction of withdrawal.

   The spacing, end distance and edge distances for wood screws should be such as to prevent splitting the wood. Lag screws should follow the rules for bolts. For further information concerning wood screws, see Wooden Boat, Issue 54 & 55 (Reference 17).

G. NAIL FASTENINGS

Hot dipped galvanized cut boat nails have traditionally and are still being used in boat building. Barbed or annular ring nails have been successful and are suitable depending upon their application (usually smaller scantling vessels). Smooth, thinly coated or plated nails, with small irregular heads and long tapered shanks such as horseshoe nails and ordinary "cut nails" (i.e. hardwood flooring nails) will not provide sufficient holding power and should not be used. In addition, wire nails are not acceptable for hull construction.

1. Lead Holes. Lead holes for nailed joints may be 3/4 of the diameter of the nail without causing loss of strength.

2. Types Of Load. If possible, nails should be loaded across the nail and not in the direction of withdrawal. This is especially important in end grain.

3. Spacing Of Nails. The end and edge distances and spacings of the nails should be such as to prevent splitting of the wood.

H. BOAT SPIKES AND DRIFT BOLTS

1. Lead Holes. Lead holes for boat spikes should be the size of the short dimension of the spike and should extend approximately 75% of the spike depth. The lead holes for drift bolts should be slightly less than the bolt diameter and of a depth equal to the bolt length.

2. Type Of Load. Where possible, spikes and drift bolts should not be loaded in withdrawal. This is especially important in end grain.

3. Insertion. A clinch ring or washer may be used under the head to prevent crushing of the wood. Spikes should be driven with the edge of the chisel point across the grain to avoid splitting the wood.

4. Spacing of Spikes and Drift Bolts. The end distance, edge distance and spacing of the spikes should be such as to avoid splitting the wood.

5. Bolts. Bolt holes should be of such diameter as to provide an easy fit without excessive clearance. A tight fit requiring forcible driving of the bolt is not recommended.

6. Placement Of Bolts In Joint. The center to center distance between bolts in a row should be not less than four times the bolt diameter

   The spacing between rows of bolts should be 5 times the bolt diameter for a bolt whose length from the bottom of the head to the inner side of the nut when tightened is 6 times the bolt diameter or longer. For short bolts, this distance may be decreased but in no case should be less than 3 times the bolt diameter.

   The "end distance" from the end of a bolted timber to the center of the bolt hole nearest the end should be at least 7 times the bolt diameter for softwoods and at least 5 times the bolt diameter for hardwoods. These requirements should be relaxed where necessary in the case of bolted planking butts to allow the "front row" of fastenings on each side of the butt to be bolts.

The "edge distance" from the edge of the member to the center of the nearest bolt hole should be at least 1 1/2 times the bolt diameter. For bolts whose length is over six times their diameter, use one half the distance between bolt rows and in no case below 1 1/2 times the bolt diameter.

For perpendicular to the grain loadings (joints at right angles), the edge distance toward which the load act, should be at least 4 times the bolt diameter.

I. BOLTING GROUPS

In general, all groups of bolts should be symmetrical in the members. The individual fastenings should be offset slightly as necessary to avoid placing more than one on the same grain.

1. Washers. The importance of washers, especially under the heads of fastenings which may be loaded in tension either because of external stresses or because of swelling stresses, cannot be overstated. The weak link in most metal-fastened wood structures is not the tensile strength of the wood or of the fastenings, nor the withdrawal resistance of threaded fastenings. The weak link is almost always the cross-grain crushing strength of the wood under the heads of the fastenings. Care should be exercised in drawing nuts down on the bolts too tight and crushing the wood.

2. Wickings. A suitable wicking should be fitted in way of the faying surface of the joint at each through bolt subject to moisture.

APPENDIX A-4

CHAPTER 4: GUIDE TO INSPECTION

A. GENERAL

Intelligent inspection of wooden vessel construction requires knowledge and judgment. Inspection is made to determine that the vessel is safe and has a reasonable chance of remaining so until the next scheduled inspection. A good basic knowledge of wood construction and the deficiencies to which it is susceptible is essential.

B. WHAT TO LOOK FOR

Problems in wooden vessels group themselves into three categories:

1. Time
   a. Decay
   b. Wood Borers
   c. Corrosion

2. Stress
   a. Cracks
   b. Broken members
   c. Failure of fastenings
   d. Failure of caulking

3. Damage
   a. Hull damage due to collision, grounding or to normal wear and tear

C. STRUCTURAL PROBLEMS

In wooden vessels structural problems develop in nearly new vessels as well as in older ones. Deterioration, especially that caused by decay and wood borers, can occur with surprising rapidity. Boats which have been free of such infestations can become infected with slight changes in service area or operation. Fastening problems in new wooden vessels can also develop as a result of several types of corrosion.

Poor selection of wood structural materials or lack of ventilation will often make themselves known in the first year of a vessel's service life. That the vessel was sound at its last inspection has less bearing on the present condition of a wooden vessel than on one of steel.

D. CONDITION OF VESSEL FOR INSPECTION.

If practicable, inspect the vessel out of the water with the interior of the hull opened up as much as possible. The bilges and forepeak should be dry and reasonably clean. Excess tackle, tools

and gear which might interfere with proper inspection should be cleared away. This is not always possible; however, hard to inspect (and thus hard to maintain) areas should not be missed.

Where the interior of the hull has closely fitted ceiling or paneling, sufficient access should be provided to allow examination of the interior at selected locations. This can be accomplished on lighter scantling vessels by cutting inspection openings in the ceiling which will also aid in providing ventilation to combat dry rot. On heavy timbered vessels, borings or core samples may be used to show the condition of hidden structures. Apparent soundness of the ceiling should not be taken as indicative of soundness beneath.

In some cases access for frame inspection may be made by removal of sheer/waterline and/or garboard planks for inspection from the outside. In any case, visual inspection must be accomplished to ascertain conditions under ceilings. Full ceiling vessels often lack ventilation between frames therefore making them a likely place where decay can be found.

Some vessels will be found with poured concrete, ballast ingots or other interferences which make internal bilge inspection and condition of floor frames/fastenings and keel bolts difficult to evaluate. Where it is possible to remove some of the material without damaging the hull or internal structural members, sufficient access should be made for examination. Careful documentation of conditions found must be accomplished to avoid unnecessary removal of internals.

The vessel's underwater body should not be filled, faired or painted before it is examined. Coatings cover a multitude of defects such as cracks, bleeding or loose fastenings, discolored wood due to rot, and borer attack.

E. VISUAL INSPECTION

An overall examination of the hull of a wooden vessel which has been in service can give the inspector an idea of the portions where deficiencies can be expected. Distorted planking, pulled butts, local damage, and unexplained wetness or weeping are tell tale indications.

Particular attention should be paid to the garboard area, stem, stern, transom, region under the covering boards, the wind and water area, and around hull fittings. It is impossible to list each area of trouble in each type of boat In general, areas which are hard to maintain, have poor ventilation or are subject to heavy stresses display the most deficiencies.

APPENDIX B

THE WOOD HULL TEST FIXTURE

OVERVIEW

After a casualty in 1993 involving a wood-hulled inspected passenger-carrying vessel, the Coast Guard reassessed its procedures for inspecting certificated wooden vessels. An advisory panel, the Joint Industry/Coast Guard Working Group on Wooden Boat Inspection, was convened in July 1994 to advise the Coast Guard on how to improve wood vessel inspections. The guidance provided by the Working Group was incorporated into Navigation and Vessel Inspection Circular (NVIC) 7-95, a revision of the earlier NVIC 1-63.

The casualty which led to the changes in policy was caused by the failure of corroded steel nail plank fastenings. One of the provisions of NVIC 7-95 is more thorough monitoring of the condition of plank fastenings, by actual removal of fasteners, with a recommended schedule for fastener inspection. Many of the vessels subject to inspection are fastened with steel nails, which generally cannot be removed for inspection without the destructive removal of the planks they fasten. Removing and replacing planks is expensive and involves considerable lost revenue time for the vessels affected. This problem has led the Coast Guard to investigate the possibly of non-destructively evaluating the condition of nails and other fastenings without removing them.

Under this contract, a test fixture was designed and constructed which provides a controlled test specimen for various types of non-destructive evaluation (NDE) which might be used to assess the condition of steel fastenings in wood hulls.

GENERAL DISCUSSION OF THE TEST FIXTURE

Construction and Scantlings

The wood hull NDE test fixture is a simulated section of the underwater part of a carvel-planked wood hull, a flat section approximately two feet in the plank direction and three feet in the frame direction. There are three frames of eastern white oak (*Quercus Alba* or related species). The frames are 2 inches square on 10 inch centers. The six planks are of southern pine (loblolly pine [*Pinus Taeda*] or shortleaf pine [*Pinus Echinata*] or related species. The planks are 1-1/2 inches thick and 6 inches wide, and each plank is fastened to each frame by three primary fastenings. There are two planking butts backed by white oak butt blocks. The planking butts are fastened with galvanized steel carriage bolts and wood screws.

The planking and butt seams are caulked lightly with cotton and filled with oil-based underwater seam putty. The fixture is painted with red lead primer, and the outer surface of the planking has a coat of anti-fouling paint over the primer.

The fixture is intended to simulate the hull construction of a typical workboat of the type often used as a "head boat", or party fishing vessel. The scantlings used in the fixture would be appropriate for a vessel in the 40'-50' length range.

Terminology

For convenience, the three frames have been labeled L, M, and R for left, middle, and right, respectively, as viewed from the planking side of the fixture. The top of the fixture is the end with the two lifting eyes. The horizontal rows of fastenings (three per plank in six planks) are numbered 1 through 18. The individual fastening locations are referred to by frame letter and fastening row number, as, for example, "L3" or "R14".

Fastenings

The principal fastenings are blunt-point hot-dip galvanized cut steel boat nails. There are also hot-dip galvanized steel wood screws, hot-dip galvanized steel carriage bolts, and type 304 stainless steel annular thread "ring" nails. A number of the boat nails, screws, and bolts have been intentionally altered to simulate deterioration by corrosion. In addition, there are locations in the fastening scheme with missing fasteners, and there are also several additional fasteners, as would be found when a nail-fastened hull has been refastened. A short section of one frame is gouged out ("guttered") to simulate the deterioration of the wood around fasteners which often accompanies advanced rusting of steel fastenings.

A steel strap is provided which can be bolted to a section of one frame to simulate a typical repair technique which might interfere with NDE identification or assessment of fasteners. Several lengths of inner sheathing (ceiling) are also provided, which can be nailed to the back of the frames, after the initial tests have been conducted, so that any interference effects caused by the ceiling fastenings can also be evaluated. In several locations, steel boat-nail fastenings with simulated corrosive reductions in cross-section have been "refastened" with stainless steel ring nails and galvanized steel wood screws placed in close proximity to the original nails.

The fasteners are staggered to follow typical boatbuilding practice. The fastenings are placed alternately 5/16" to one side and the other of the center of the frames, beginning with the top fastenings in each frame to the right of the centerline. Where secondary fastenings have been installed, they are in the alternate or "off-stagger" positions, and if they at the edges of the planks, they are slightly farther from the plank edge than the primary fastenings. Figure 1 shows the primary fastening positions and also shows the positions of secondary fastenings, where they exist.

There are two types of carriage bolts in the fixture, smooth-shanked and full-thread. Samples of both have been provided. All of the butt block bolts are smooth-shanked, while some of the plank-frame bolts are full-thread. The smooth-shank bolt is traditional, but recently they are becoming harder to obtain because the full-thread type is cheaper to produce. The smooth shank bolts are more suitable for marine use, since the threaded part of the shank does not cross the plank-frame joint, where corrosion is often most severe. Full thread bolts are denoted in the plank fastening charts by the note "FULL-THREAD".

Lead Holes for Fasteners

All of the fasteners in this fixture are installed with drilled lead holes. The lead holes for nails and screws are generally stepped holes; a larger shank hole in the plank for the fastener shank and a smaller pilot hole in the frame or butt block for the lower part of the fastening. The shank and pilot hole sizes for various fastenings are as follows:

For Boat Nails (Nondefective and Defect N1)	
Shank hole	.188 (3/16)
Pilot hole	.141 (9/64)
For Boat Nails with Defect N2	
Shank and Pilot Holes	.250 (1/4)
For Wood Screws (nondefective)	
Shank Hole	.266 (17/64)
Pilot Hole	.188 (3/16)
For Wood Screws (Defect S1)	
Shank Hole	.266 (17/64)
Pilot Hole	.219 (7/32)
For Wood Screws (Defect S2)	
Shank Hole and Pilot Hole	.266 (17/64)
For all Bolts	
Through Hole	.313 (5/16)
For Ring Nails	
Shank Hole	.188 (3/16)
Pilot Hole	.141 (9/64)

Fastener Head Counterbores

The heads of all fastenings in the fixture are counterbored 3/8" to 7/16" below the plank surface. Most of these counterbores are filled by wood plugs ("bungs") cut from the same boards from which the planking was cut. These plugs are set in urea-formaldehyde water resistant glue. The counterbore sizes are as follows: 3/4" for carriage bolts, 5/8" for wood screws, and ½" for boat nails and ring nails.

In order to evaluate possible interference of head-covering materials other than wood with NDE techniques, the counterbores over the heads of several of the non-

defective boat nails, wood screws, and ring nails are filled with three non-wood substances: 1. polyester auto body putty; 2. epoxy glue thickened with colloidal silica and phenolic microballoons; and 3. oil-based underwater seam putty.

A detailed chart of fastener locations and defect types is provided at the end of this document. This chart shows defect types, head coverings, and the locations of secondary "refastening" screws and nails. Labeled samples of each type of non-defective and defective fastener are provided, along with an example of the "guttered" frame containing the simulated deteriorated wood used in the guttered frame and in defective fastenings of the "N2" and "S2" types.

SIMULATED DEFECTS

The deterioration of a steel fastening in a wood hull is difficult to simulate accurately. As the fastenings age, the zinc coating (galvanizing), which provides both physical and cathodic protection to the underlying steel slowly corrodes away. When a significant area of the steel is exposed to the wet wood, the corrosion rate increases. The corrosion not only decreases the effective cross-sectional area and strength of the fastening, but it also decreases the fastening's holding power. The chemical changes and physical expansion of the corroding metal also damage the surrounding wood. Around a corroded steel fastener there is a gradual transition from sound wood to damaged wood, to corroded metal, and eventually to sound metal. Chemical damage due to corrosion products is usually greatest in the frames and spreads farther and more rapidly along the grain direction than across the grain, resulting in the "guttering" which is simulated in a section of Frame "R".

In constructing this fixture, decayed wood has been simulated by a mixture of a polyurethane foam adhesive and sawdust. The cured substance can be seen in the sample of a simulated deteriorated frame which is provided. This glue-sawdust mixture was used in the "guttered" section of frame R and in holes for boat nails and wood screws having defects N2 and S2, respectively. The details of these defects are described below.

Merely reducing the cross-section of fasteners is unlikely to accurately reproduce the appearance to NDE equipment of a fastener embedded in rust; likewise, the glue-sawdust mixture is not expected to simulate the damaged wood and corroded metal in the transition area around deteriorated fasteners very well. Therefore, the fixture should be used primarily to assess the effectiveness of the NDE for the following tasks:

- Qualitatively, identifying the existence, exact location, and the number of fasteners in an area where fasteners are expected to be.
- Qualitatively, identifying the type of fastener (nail, screw, etc.)

- Quantitatively, evaluating localized reductions in the effective cross-section of the fasteners.

Defect Types

Defect types for the various types of fasteners are listed below. These defects are identified on the fastening chart.

Note that the effects of reductions in the diameter of fasteners are not linear. A reduction to one-half the original diameter is a reduction of 75% of the cross-sectional area and strength. For a screw, the root diameter of the threads is about 2/3 the shank diameter, so a reduction to 2/3 of the original diameter in the thread area may cause a complete loss of holding power.

The shanks of steel fasteners of all types typically rust more rapidly than do the heads. This is partly because the frames, which are often oak, present a more corrosive environment for the galvanizing and later for the underlying steel than does softwood planking, and partly because the plank-frame joint is a susceptible location at which the metal ions produced during corrosion can more easily diffuse away, allowing the corrosion to continue. Accordingly, the types of defects simulated for bolts, screws, and nails in this test fixture do not include severely corroded heads.

For cut boat nails:

Defect Type N1 - The nail has been reduced locally to about one-half its original diameter. The reduced area is about ½" long, centered approximately at the location of the plank-frame interface, and tapers to the original diameter at both ends.

Defect Type N2 - The part of the nail in the frame has been ground to about one-third its original diameter at the end, tapering to the original size near the plank-frame joint. The pilot hole and the shank hole are both 1/4" in diameter, and the space around the ground point is filled with the glue-sawdust mixture that simulates deteriorated wood.

For Wood Screws:

Defect Type S1 - The screw has been reduced locally to less than its root diameter over about ½" at the plank-frame joint, which corresponds roughly with the top of the threads.

Defect Type S2 - The screw has been reduced to less than the root diameter at the end of the threads, tapering to slightly more than the root

diameter at the top of the threads. The thread pilot hole is the same diameter as the shank hole and the space around the ground-off threads is filled with the glue-sawdust mixture.

For Carriage Bolts:

Defect type B1 - The bolt shank has been reduced to about one half its original diameter locally near the location of the plank-frame interface. The reduced area is about 1/2" long, and tapers to the full shank diameter at each end.

Defect type B2 - The bolt shank has been reduced to about one-half its original diameter at the location corresponding to the inside of the frame, tapering to the original diameter about 1 inch further up the shank.

For Ring Nails:

There are no simulated defects in the ring nails in the test fixture.

Metal Backing Strap

The steel backing strap on frame L between fastening locations L1 and L9 simulates a commonly encountered frame reinforcement technique. It is fastened by three bolts, but there are nails and screws under it as well. The strap was included out of a concern that its presence might interfere with NDE testing of the fastenings under it. The strap is fastened by bolts at L1, L5, and L9. It can be removed easily by removing the nuts on those three bolts, prying off the strap, and replacing the nuts and washers directly on the back of the frame.

"Guttered" Area in Frame "R"

Frame R between locations R8 and R11 has been gouged out ("guttered") about 1 inch deep and one-half inch wide, following the stagger of the fastenings. The guttered area has been filled with a loose mixture of sawdust and a low-expansion polyurethane foam adhesive to simulate the deteriorated trough of wood that often forms as a result the advanced rusting of a row of steel fastenings. Such a trough is often invisible from the back of the frame, even when the deterioration is so bad that the fastenings are completely surrounded by damaged wood. A sample of a guttered section of a frame, partially filled with the same sawdust-glue mixture used in the test fixture, is provided with the fastening samples.

Ceiling

Many boats have internal sheathing, or ceiling, inside the frames. The ceiling in smaller vessels is usually much lighter, narrower, and more lightly fastened than the planking, and ceiling planks may not be tightly fitted against one another. In larger vessels the ceiling may be similar to the external planking and may be heavily fastened, tightly fitted, and caulked. Enough ceiling has been provided to cover most of the lower half of the fixture. This ceiling is provided loose.

The concern with ceiling is that the ceiling fastenings, which are typically light galvanized nails for ceiling of this size, might interfere with NDE of plank fastenings. After an initial round of tests has been completed, the ceiling can be fastened in place and the tests can be repeated, which will allow an assessment of the effects of the ceiling fastenings on the NDE results. The ceiling should be fastened with the nails provided and marked for this purpose, two to a ceiling plank at each frame. The nails provided for the ceiling have a gauge of .125". Full-depth pilot holes 3/32" or 7/64" in diameter should be drilled for the ceiling nails before they are driven. If the ceiling needs to be removed intact and used again, fasten it in place with galvanized drywall screws, with steel or stainless steel wood screws, or with double-headed staging nails instead of with the nails provided. In any case, the ceiling fastenings should be driven without regard to the positions of the underlying plank fastenings, in accordance with typical workboat construction practices.

Deck Screws

Another type of fastening which inspectors might need the ability to detect by NDE is the "Deck Screw". These are slender screws, a hot-dip-galvanized version of drywall screws, made of hardened steel with bugle heads, root-diameter shanks, and sharp points, designed for laying residential outdoor decks. These screws are not appropriate for use in boat construction because they are brittle, have minimal corrosion allowance in the very slim body, and the high-carbon steel from which they are made corrodes rapidly if the galvanizing is compromised. While there are no deck screws in the fixture, they could be easily installed, and since they are not appropriate for marine use, it might be a useful test to try to detect them.

Plank Deterioration

An area on the back of the second and third planks (from the top) between frames L and M has been reduced in thickness to simulate deteriorated planking. The plank thickness has been reduced to about I inch in the center of this area, and the thickness tapers out to the full plank thickness at the edges of the area. The area is readily visible on the back of the planking.

CONDITIONING THE FIXTURE

Wooden Small Passenger Vessels are typically inspected during a short maintenance haul-out, usually in the spring. During such a haul-out the moisture content of the planks and framing will remain at approximately the same level as when the boat is in the water. Since the moisture content of wood can have a significant effect on the transmission of various types of signals through it, the test fixture should be conditioned to an appropriate moisture content before testing.

Wood absorbs water in two ways. Water is taken into the walls of the hollow wood cells, where it forms molecular bonds with the wood material. This water is referred to as the "bound water". All water absorbed by wood up to a moisture content of about 29% (that is, 29 parts water to 100 parts dry wood by weight) is quickly taken up by the cell walls and becomes bound water. The moisture content at which the cell walls are saturated with bound water, the aforementioned 29%, is called the *fiber saturation point.*

The moisture content of wood exposed to air will eventually come into equilibrium with the relative humidity of the air. The moisture content of wood in contact with air will vary from bone dry (0% M.C.) at 0% relative humidity to the fiber saturation point at 100% relative humidity.

Water can also fill up the hollow cell cavities of wood once the fiber saturation point has been reached. This additional moisture is called the "free water". Wood in contact with humid air may reach the fiber saturation point but it will not contain any free water. However, wood in contact with liquid water may take up significant amounts of free water. The maximum moisture contents of boatbuilding woods in contact with water range from just slightly greater than the fiber saturation point for some cedars to 100% or more for baldcypress. (100% moisture content means one hundred parts water, by weight, to 100 parts dry wood).

Since fastener corrosion problems are always worse underwater than above, the test fixture should be conditioned to represent an underwater section of a hull. For a hull like the test fixture, the underwater planking, which is in contact with water, will typically be at or near its maximum moisture content, while the internal framing, which is not normally immersed in water, will be at a moisture content near fiber saturation.

Rapid changes in moisture content in either direction should be avoided, since damaging stresses will occur if the planks and frames of the fixture are not allowed to respond evenly throughout their thickness to changes in the external conditions.

The ideal conditioning environment for this fixture is with the outside surface of the planking in contact with water and with the back or frame side in a high-humidity environment but not actually wet. This can be achieved by lining the shipping crate with plastic film, placing the fixture plank side down against wet burlap or rags laid on the

plastic, and keeping the cover closed to ensure a humid atmosphere for the frame side. It may take several weeks to achieve a realistic moisture content.

The planking and frames can be tested with a moisture meter to evaluate the success of the conditioning procedure. Note that if a salt water is used to condition the fixture, readings taken with a resistance-type moisture meter will not be accurate. Whether salt or fresh water is used, a small amount of chlorine bleach may be added to the water to prevent mold and mildew from forming.

THE FASTENING CHARTS

Two fastening charts are provided, one for plank-frame fastenings and one for the two plank butts. The charts show the type of fastening at each location in the fixture, along with types of defect and head treatments. Secondary plank-to-frame fasteners, where they exist, are listed below the primary fastener, and are denoted by an asterisk; these fasteners are in the "alternate" position in the staggering scheme.

Defect types correspond to those listed above for each fastening type. A dash indicates a non-defective fastener. Counterbores are filled by wood plugs (bungs) denoted by "BUNG"; epoxy putty, denoted by "EPOXY"; polyester body-filler putty, denoted by "POLY"; and oil-based underwater seam compound, denoted by "PUTTY".

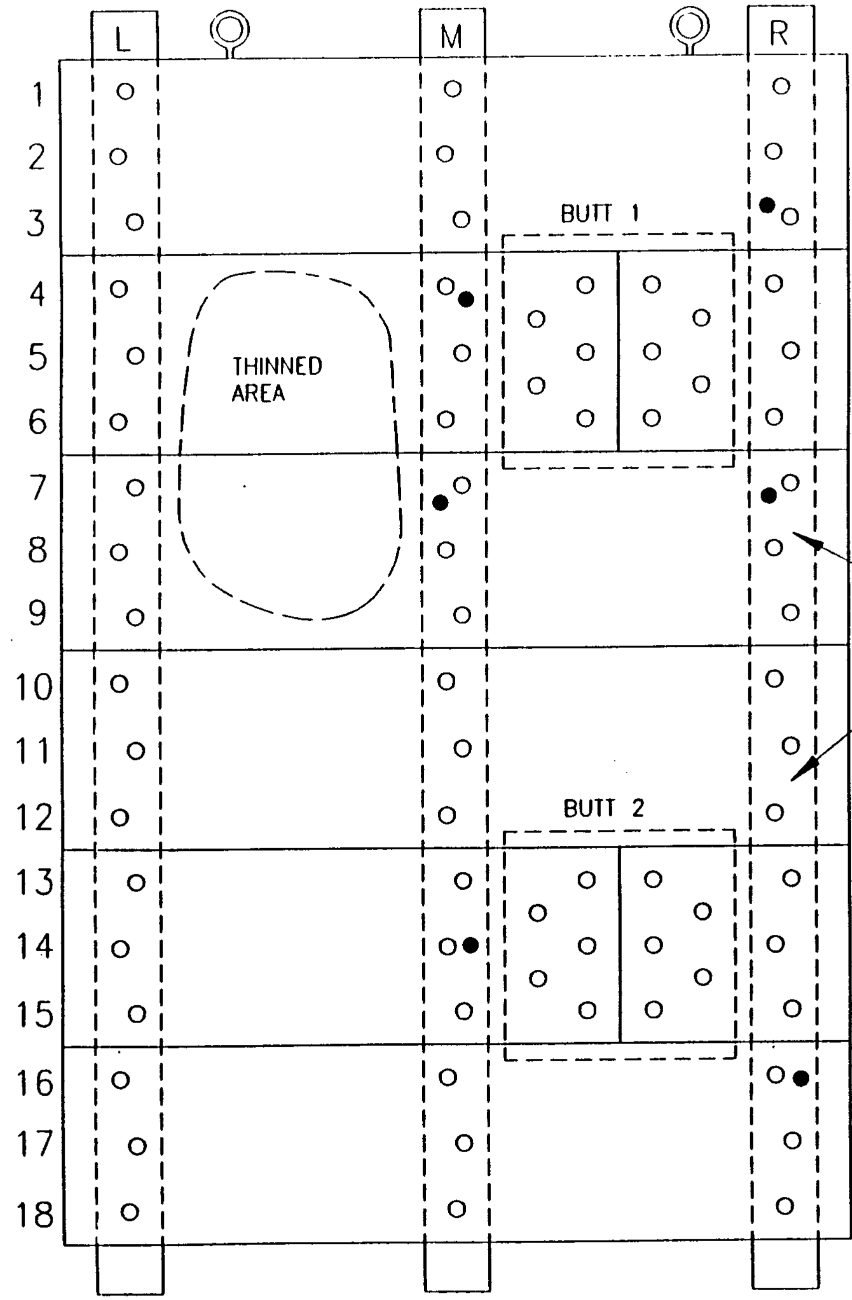
ENCLOSURES:

Figure 1 - (1 letter-size sheet)
Front view of the fixture showing fastening locations and basic dimensions.

Plank Fastening Chart - (2 legal aixe sheets)
Shows fastening types, defect types, head treatments, and locations of secondary fasteners

Butt Fastening Chart - (1 letter-size sheet)
Shows defect types.

Questions about this fixture can be directed to Ed McClave of McClave, Philbrick & Giblin. Mr. McClave may be reached at the MP&G shop; 43 Wilcox Rd., Stonington CT, 06378 phone 860-572-7710, or at his office; 45 Church St., Noank CT 06340 860-536-4180.



PLANKING 1-1/2" THICK SOUTHERN PINE
FRAMES 2" X 2" WHITE OAK
BUTT BLOCKS 1-1/2" THICK WHITE OAK

BOLTS 5/16" GALV. STEEL
SCREWS #16 (.268") GALV. STEEL
BOAT NAILS 1/4" (NOM.) X 2-1/2"
RING NAILS 8 GA. X 2-1/2"

OVERALL DIMENSIONS OF PLANKING 24" X 36"

○ PRIMARY FASTENING POSITIONS

● SECONDARY FASTENING POSITIONS

REMOVABLE 3/16" X 1-1/2" STEEL BACKING STRAP
FITS BETWEEN POSITIONS L1 AND L9

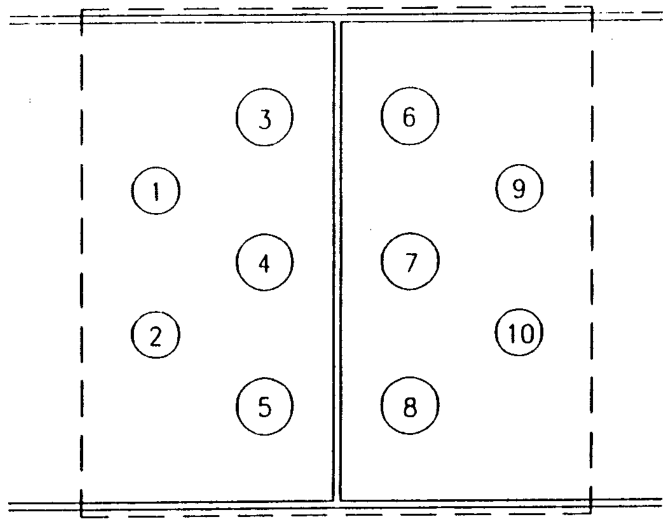
"GUTTERED" AREA

MP&G

TEST FIXTURE
FOR USCG

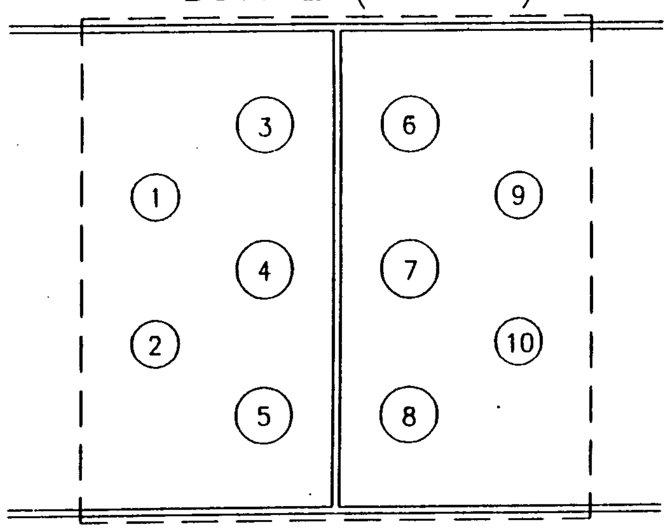
McCLAVE, PHILBRICK & GIBLIN
STONINGTON, CONNECTICUT

BUTT 1 (TOP)



FASTENING POSITION	FASTENING TYPE	DEFECT TYPE
T1	SCREW	S2
T2	SCREW	--
T3	BOLT	–
T4	BOLT	B1
T5	BOLT	B2
T6	BOLT	B2
T7	BOLT	–
T8	BOLT	B1
T9	SCREW	S1
T10	SCREW	–

BUTT 2 (BOTTOM)



FASTENING POSITION	FASTENING TYPE	DEFECT TYPE
B1	SCREW	–
B2	SCREW	S1
B3	BOLT	–
B4	BOLT	B2
B5	BOLT	–
B6	BOLT	B1
B7	BOLT	–
B8	BOLT	B2
B9	SCREW	S2
B10	SCREW	–

PLANK FASTENING CHART

FASTENING NUMBER	FRAME L			FRAME M			FRAME R		
	FAST-ENING	DEFECT	HEAD	FAST-ENING	DEFECT	HEAD	FAST-ENING	DEFECT	HEAD
1	BOLT	—	BUNG	BOLT	—	BUNG	BOLT	—	BUNG
	(TOP OF METAL STRAP)			(FULL-THREAD BOLT)			(FULL-THREAD BOLT)		
2	NONE	—	BUNG	RING NAIL	—	BUNG	NAIL	N1	BUNG
	COUNTERBORE AND SHANK HOLE, BUT NO PILOT HOLE; NO FASTENER								
3	NAIL	—	BUNG	SCREW	—	BUNG	NAIL	N2	BUNG
							* RING NAIL	—	POLY
4	SCREW	S1	BUNG	NAIL	N2	BUNG	NONE	—	BUNG
				* RING NAIL	—	EPOXY			
	(THIS SCREW BROKE AT THE REDUCED AREA WHEN IT WAS DRIVEN)						COUNTERBORE, SHANK AND PILOT HOLE; NO FASTENER		
5	BOLT	B2	BUNG	RING NAIL	—	BUNG	BOLT	B2	BUNG
6	NAIL	N1	BUNG	NAIL	N1	BUNG	NAIL	N2	BUNG
7	SCREW	—	BUNG	NAIL	—	PUTTY	NAIL	N2	BUNG
							* RING NAIL	—	POLY
8	NAIL	N2	BUNG	NAIL	—	BUNG	NAIL	N2	BUNG
							FRAME "GUTTERED OUT"		
9	BOLT	B1	BUNG	NAIL	N2	BUNG	SCREW	S2	BUNG
	(BOTTOM OF METAL STRAP)						FRAME "GUTTERED OUT"		

FASTENING NUMBER	FRAME L			FRAME M			FRAME R		
	FAST-ENING	DEFECT	HEAD	FAST-ENING	DEFECT	HEAD	FAST-ENING	DEFECT	HEAD
10	NAIL	-	POLY	BOLT	B1	BUNG	SCREW	S2	BUNG
							FRAME 'GUTTERED OUT'		
11	NAIL	N1	BUNG	NAIL	—	BUNG	NAIL	N2	BUNG
							FRAME 'GUTTERED OUT'		
12	NAIL	N2	BUNG	BOLT	—	BUNG	NAIL	—	BUNG
13	NAIL	—	EPOXY	NAIL	—	EPOXY	NAIL	N1	BUNG
14	NAIL	N1	BUNG	NAIL	N2	BUNG	NONE	—	—
				* RING NAIL	—	POLY			
							NO HOLES, NO FASTENER		
15	NAIL	—	BUNG	BOLT	B2	BUNG	NAIL	—	BUNG
16	SCREW	S1	BUNG	NAIL	—	POLY	NAIL	N2	BUNG
							* SCREW	—	EPOXY
17	SCREW	S2	BUNG	NAIL	N1	BUNG	NONE	—	—
							NO HOLES, NO FASTENER		
18	BOLT	—	BUNG	BOLT	—	BUNG	BOLT	—	BUNG
				(FULL-THREAD BOLT)			(FULL-THREAD BOLT)		

[BLANK]

APPENDIX C
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APPENDIX D
McCLAVE MARINE

ANALYSIS OF THE EFFECTIVENESS OF NONDESTRUCTIVE EVALUATION OF A WOODEN HULL

by
Edward F. McClave

for
USCG R&D CENTER, GROTON CT
Mr. Kurt Hansen, P.E.

Order No.
DTCG32-97-F-E00034

Requisition/reference No.
2397327E00034

I. DESCRIPTION OF THE WORK

Background

Recent changes in Coast Guard inspection policies for certificated wooden boats embodied in NVIC 7-95 require direct visual examination of fasteners as specified intervals. When hulls are fastened with screws or bolts, the fastenings can usually be removed for inspection without damage to the structure. When hulls are nail-fastened, however, it is much more difficult to remove the fastenings without damaging the planks they fasten. Thus, the requirement for direct inspection of fastenings will in many cases be, for nail-fastened vessels, essentially a requirement that planks be removed destructively and then replaced with new planks, an expensive and time-consuming procedure, and one which not all boat yards have the expertise to accomplish effectively.

Along with the need to inspect fastenings, an equally important requirement is the assessment of the integrity of the structural members into which the fastenings are driven. This is especially important in the case of nails and screws, which depend completely on the soundness of the underlying structure to hold the planks on the hull. Regardless of the type of fastenings, inspection of the structure under the planking, which holds the plank fastenings, is difficult and is sometimes impossible without removing the planks. Deteriorating fastenings often damage the wood around them, so simply removing old fastenings and replacing them with new ones is not always effective. As with the inspection of fastenings, the inspection of underlying structure is more difficult in nail-fastened boats, since it is often difficult to remove nail-fastened planks without damaging them beyond repair. By contrast, on boats with screw, bolt, or rivet fastenings, it is usually possible to remove a plank intact and then reinstall it.

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Overall Description of the Project

This project was a first attempt at nondestructive evaluation (NDE) of fastenings and wood structure in wooden vessels, with the long-term goal of providing an alternative to the removal of planking as an inspection technique. It involved tests with various acoustic and vibration technologies for evaluating the condition of wood and with two types of x-ray imaging for evaluating the condition of fastenings (and possibly also the condition of wood surrounding the fastenings).

The various NDE technologies were applied to the hull of the *VOLSUNGA III*, a 39 foot converted Nova-Scotia type lobsterboat hull which was most recently used as a ferry in the New Haven CT area, under Coast Guard certification. This hull was built of northern white cedar planking over bent oak frames, with an oak transom and stem, birch or maple keel, and floor timbers of various materials. The planking was clinch-fastened to the frames with hot-dip galvanized steel square cut boat nails about 2-1/2" long with a gauge of about 3/16". Fastenings into the stem, transom, keel, and other centerline members were similar nails, driven straight. Galvanized steel bolts and drifts were used to fasten the backbone.

After the tests were complete, the boat was dismantled, with small areas of the hull which had been subjected to various tests (primarily x-ray imaging), retained for dissection. The purpose of the dissection was to verify the effectiveness of the x-ray imaging at evaluating the condition of fastenings and of the wood surrounding the fastenings. This verification was accomplished by extracting individual fastenings from the pieces of the hull and matching them with their images on the film. Mr. Kurt Hansen of the USCG R&D Center and I (Edward McClave) performed all of the dissection and correlated the actual condition of the fastenings with their images.

A secondary benefit of the project was the ability to compare the local structural condition of the hull, which could be evaluated very accurately during disassembly, with the assessments of condition rendered by various surveyors and inspectors who evaluated the hull before it was dismantled.

The Two X-Ray Techniques

Two types of imaging were used. The first was a real-time x-ray technique developed by Science Applications International Corporation (SAIC). This system, called the Ultra-Image DRS Digital Radioscopy System uses a portable low-intensity x-ray source and an 8 x 10 inch detector. Still images are displayed in near real-time on the screen of a laptop computer at 640 x 480 pixel resolution with 256 shades of gray. The gray-scale images can be saved as digital files (about 310K bytes each) of the same resolution for later printing or image enhancement.

The images from this system were available for viewing on the screen within seconds of the shot. If a small printer was available, they could have been printed on site immediately,

however, printed images tend to be of poorer quality than the screen image. This technique yields positive images, with sound metal showing dark, corrosion products as a lighter gray, and the surrounding wood light.

The second imaging technique was a high-energy x-ray system using 14" x 17" photographic film plates. The plates are developed in a portable darkroom on site and are available for viewing about 15 minutes after the shot. This technology is similar to that used for testing welds in steel structures. The film x-ray technique yields a negative image, with good metal showing as a bright area, deteriorated metal (corrosion products) as a darker area, and the surrounding wood dark. The x-ray technicians provided a listing which gave their assessment of the condition of the fastenings for which there were images of adequate quality.

Comparison of Characteristics

The real-time x-ray equipment images a considerably smaller area than the film-type system. This is not necessarily a disadvantage; since the real-time detector is smaller than the film, this makes it possible in some cases to place it closer to the target. The quality of images is better with either system when the detector or film is closer to the target.

The real-time equipment is considerably more portable (two large suitcases), which allows more flexibility in setting up shots in the usually restricted space inside a hull. The low-energy characteristics of the real-time system mean that a much smaller danger area has to be cleared of personnel before each shot is taken than with the film-type system.

Cost is a function of both time on site and number of shots with the film-type system. With the real-time system, the cost is primarily a function of time on site. This, combined with the rapid re-imaging time and more portable nature of the real-time system, makes it possible to view an image, then quickly re-adjust the viewing angle, detector position, and source energy output to produce a better image.

If the real-time system could achieve image quality equal to the film-type system, it would be clearly superior for wood boat inspection.

Comparison of Images

During the first trial in the field, the real-time system was very effective at locating fastenings but not very effective at showing their condition. During the later laboratory trial the system showed considerably more success at indicating fastener condition.

The film-type system gave good images during the field trial although there were some problems with exposure levels,. These images showed subtle but readable differences in image intensity between the badly corroded and less badly corroded parts of fasteners, and dissection of the imaged areas of the hull proved that these differences definitely correlated to the condition of the fasteners.

Procedures Used for Dissecting the Hull Sections

The primary purpose of this part of the project was to assess the effectiveness of x-ray imaging in evaluating the condition of the fastenings. We worked exclusively with film images, as the real-time images available from the first trial at the boatyard did not appear to contain any usable information about condition. In order to conduct this assessment, we attempted to identify individual fastenings which appeared on the x-ray images and to extract them from the structure without further damage so that the actual condition of each fastening could be compared to its x-ray image and then compared to the x-ray technician's recorded assessment of the condition of that fastening.

After the NDE exercises on the hull at the boatyard were complete, we marked out, with paint, the areas which had been imaged on x-rays, and several other areas of interest. In all of these areas, plank numbers were assigned and marked on the planking to aid in establishing the exact locations of the sections during later analysis. The hull was cut up by another contractor, the boatyard owner, leaving the marked sections, which we moved to Groton for dissection.

The film x-ray contractors numbered the individual fastenings on a number of the film-type x-ray images, and provided a listing of the numbered fastenings with their assessment of condition, based solely on the x-ray images. Using the film-type x-ray images as a guide, we attempted to identify on the hull sections all of the fastenings which had been numbered and evaluated by the x-ray technicians. We were eventually very successful at correlating individual fastenings with their images, although in a number of cases it was only after actually extracting a fastening and others around it that we were able to conclusively identify it, often using clues such as varying lengths, the angles at which the fastening or its neighbors were driven, and other information which was not available on the surface.

The fastenings from the planking into the stem, the transom, and the keel were extracted by carefully splitting away the surrounding planking with a chisel, disrupting the fastening as little as possible. Once the head and the part of the shank which had been in the planking was exposed, the head was gripped with "Vise-Grip" type locking pliers and pried out of the wood into which it was driven.

In several cases, the wood around corroded fastenings was also saved in order to evaluate the amount of damage that a deteriorating steel fastening does to the wood in contact with it and to determine if x-ray imaging might detect this damage.

The areas from which fastenings were extracted were:

- Plank fastenings from the forward plank ends into the lower part of the stem, at, just above, and just below the painted waterline. These fastenings were galvanized steel boat nails of two sizes, driven straight into the back rabbett of the stem and into the stem knee behind the stem. There were two usable film x-ray images of this area. About thirty fastenings from this area were definitely identified on the x-rays and extracted.

- Plank fastenings into the transom edge at the port quarter near the turn of the bilge. At, just below, and just above the painted waterline. These fastenings were galvanized steel boat nails driven straight into the transom edge. There was one good film x-ray image of this area. About fifteen fastenings from this area were identified on the x-rays and were extracted.

- Plank fastenings from the lowest three strakes into the frame heels and into the keel rabbett midships on the port side, including the midship butt in the garboard strake, the associated frames, one floor timber, and a section of the keel. These fastenings were all galvanized steel boat nails. The plank-to-frame fastenings, including the upper fastenings in the butt of the garboard plank, were boat nails, driven through the frames and cliched on the inside. The plank-to-keel fastenings, including the bottom row in the butt of the garboard, were driven straight into the back rabbett of the keel. There were two usable film x-ray images of this area. About ten fastenings from this area were identified on x-rays and were extracted.

- Two transverse slices through the horn timber, stern deadwood and keel, each containing two vertical bolts in the structure. These bolts were 5/8" diameter galvanized steel bolts, on either side of the shaft hole in the deadwood, originally having nuts at both top and bottom (some of the nuts at the bottom ends of these bolts were missing). There were no good x-ray images of these bolts, although one showed partially on another image.

Condition of Fastenings

- The condition of the fastenings in the stem area ranged from good to moderately corroded. The wood of the planking and of the stem in this area was generally sound. The heads and the parts of the shanks of the corroded fastenings which were in the planking were generally in good condition, with the parts of the shanks embedded in the stem timber necked down from corrosion.

- The condition of the fastenings from the port quarter ranged from good to mildly deteriorated. The wood of the transom and of the planking in this area was generally sound. The pattern of corrosion of these fastenings was similar to those in the stem.

- The condition of the fastenings in the lower port area of the hull ranged from moderately deteriorated to completely corroded away beyond the inner plank surface. Some of the clinched nail ends inside the frames were intact despite the part of the nail in the frame being completely gone. Many of the clinch-nail fastenings in the lower section of the hull between planks and frames and the straight fastenings from the lower edge of the garboard into the back rabbett of the keel were so badly corroded that only the heads and the part of the shank which was in the planking remained.

  The planking and the keel in this area were sound; the frame heels were old and tired, not biologically deteriorated but severely weathered from the effects of long-term immersion

with protective coating of paint, and fractured from the effects of the severe bend in the lower bilge area.

- The keel bolts were corroded, unevenly, with the worst parts down to about 65% of the original diameter (which is about 40% of the original cross-sectional area).

II. CONCLUSIONS and RECOMMENDATIONS

Effectiveness of X-Rays at Indicating the Condition of Fasteners

The fastenings extracted from the test hull ranged in condition from almost like new to completely corroded away, leaving only an empty pilot hole full of rust. The film-type x-rays proved capable of evaluating the condition of fastenings quite reliably throughout this broad range. The images showed a subtle but clearly distinguishable difference between solid metal and the corrosion products surrounding the solid metal in those images which had a good exposure level.

Parts of the nails which were completely corroded away inside the frames or keel, leaving only holes with corrosion products, showed as darker sections in the image. In cases where the shank was merely reduced from corrosion, the necked-down area was quite clearly distinguishable from a darker-colored halo of corrosion products around it, and reading the image gave a useful approximation of the amount of corrosion present. It is clear that an experienced technician could use good quality film-type x-ray images to evaluate with considerable accuracy the condition of steel nails and bolts in wood structures, and, just as important, it is also clear that the experienced technician would be able to reliably judge whether the quality of a particular image is or is not good enough to allow its use for this purpose. In many of the plates there were both overexposed and underexposed areas. Only in areas with correct exposure could the condition of fastenings be reliably determined. The written evaluations of fastener conditions provided by the film x-ray technicians were, in general, very accurate, and there were no flagrant "false positives" or "false negatives".

The film-type x-ray was very effective at identifying both the presence of fastenings and their condition. The real-time x-ray was also effective at identifying fastening types and positions, but during the tests conducted at the boat this technique was not able to discriminate solid metal from corrosion products. During the later laboratory test at Groton on sections of the hull, the real-time technique did successfully image several badly corroded plank-frame clinch nails in the garboard butt area from the starboard side and showed a subtle but distinguishable difference between the parts of the shanks in the planking and the bent-over clinches on the inside of the frames, which were relatively uncorroded, and the badly corroded part of the fastenings in the frames. These images were of nearly the same quality as those obtained of the same area by film x-rays at the first trial. However, it should be noted that during this second trial, the planking had been separated from the rest of the structure and the real-time detector was placed right up against the structure, while in the field, using film-type x-rays, the same area had to be imaged by shooting straight through the entire hull at a film plate located on the other side of the boat, a much more realistic situation. The films taken under these conditions showed usable images, although over only a small part of the plate.

Effectiveness of X-Rays at Indicating the Condition of the Wood Near Fasteners

There was very little badly damaged wood around fastenings that could be attributed to the corrosion of the fastenings, even around those fastenings which were completely corroded away. In addition, there was very little wood deteriorated for other reasons in the areas for which images were available. Despite this hull not being a very good test bed for evaluating x-ray evaluation of wood damage, it appears that the film-type x-rays do not show enough detail to reliably evaluate the condition of wood, at least when the exposure level is adjusted for optimum imaging of metal. It is possible that if the exposure level were adjusted with the intention of showing detail in the wood rather than the condition of metal, the images might be more useful in evaluating the wood.

Certain features of wood parts of the boat were faintly but definitely discernible in the film-type x-rays. The actual grain of the wood was visible in many images, although it is questionable whether different species could be differentiated or condition could be inferred. The putty in the plank seams was clearly visible, and being able to see seams is a great aid in identifying individual fastenings. In cases where two wood parts crossed at right angles, for example, planks and frames, the wood grain could be seen running in both directions, superimposed. In one case, a clearly visible line running along a plank, which looked like a seam, but was in the wrong place for a seam, turned out, on inspection of the cut-off end of the plank, to be a particularly dense, resinous area of the wood a few annual rings out from the heart of the tree. In a realistic situation the end-grain of the plank would most likely not be accessible to clear up such confusing images. The checks and seams in the transom were clearly visible, most likely because of the putty in them.

During the first trial, the real-time x-rays did not show any usable details of the wood structure. Several real-time x-ray images of the aft deadwood looking at the end-grain, taken during the laboratory trial in Groton, did clearly show the grain patterns and checks in the wood.

Problems with X-RAY Imaging and Recommendations for Solving Them

Correlating Fasteners in Hull with Their Images on Film

With virtually every image, it was very difficult to quickly correlate the images of individual fastenings with the actual fastenings. In the case of plank-to-frame and plank-to-backbone fastenings, the viewing angle is not perpendicular to the hull surface. This angled perspective is absolutely necessary so that the shanks of the plank fastenings, which are perpendicular to the surface, appear in profile, the only view which gives any useful information about condition. In addition, the hull structure places physical constraints on the position of the film and of the source which in many cases results in a viewing angle that is not in a horizontal plane. The compound viewing angle makes it difficult for a person reading the film to establish the position and orientation of features shown in the image.

The images of the stem presented another problem with identifying individual fastenings. Physical constraints required that the viewing angle through the most interesting part of the stem, the lower part, be far from horizontal. Because the back rabbett of the stem was fairly deep, the plank-to-stem fastenings were not all at the same distance from the plank ends at the stem rabbett. A number of the plank-end fastenings were two or more inches back from the actual plank end, and some were even further back where the forefoot knee backed up the stem and some fastenings were driven into it. Due to the viewing angle and the spread of fastening positions fore-and aft, the top-to-bottom order of fastenings in the image did not necessarily correspond to the actual top-to-bottom order in the stem. This problem made it very difficult to positively correlate individual fastenings with their images. We did eventually manage to establish a definite correlation, but only after using clues available from dissecting the area, clues which would not be available to inspectors in the field. In addition, the two views of the stem were taken at different horizontal angles, which made correlation of individual fastenings between the views difficult.

It should be noted that while identification of individual fastenings was critical to this project in order to verify the effectiveness of the imaging technique, during an actual inspection in the field, the goal would most likely be the assessment of the overall condition of the fastenings, and individual identification, although always desirable, would probably not be totally necessary.

However, in a few cases during these tests, we found it difficult to match images with even the general area of the hull they represent. In a field inspection, this level of accuracy is essential. The following section presents some recommendations for ensuring that images can later be accurately matched to the areas of the hull they represent.

Recommendations for Matching Images to the Hull

For this rather expensive imaging technique to be used efficiently and for the resulting images to be easily correlated with the hull structure, considerable effort must be devoted to setting up each shot and great care must be taken to record the exact circumstances of each image. My recommendations for recording images are:

- Many surveyors or inspectors routinely number each plank and frame line during a detailed survey. This should be done for x-ray imaging also, at least in areas to be imaged (chalk works well for this, and does not damage the hull or its finish). This numbering will allow each plate to be identified positively by its general position in the hull.

- Each image should be given a unique number. If it is at all possible, the hull surface should be marked with this number in such a way that it will show up on the image. Adhesive-backed metallic foil numbers would probably work for this purpose. Numbers which appeared directly on the image would positively eliminate any question of films or negatives being interchanged.

- The approximate center aiming point of each image should be recorded in a notebook, at the time the image is taken. The point should be identified by image number, side of vessel, plank number, and frame number, for example "X-ray 12, starboard, plank 1, frame #26.

- The approximate horizontal and vertical angles of view should be recorded in an unambiguous manner, for example, (as in "Starboard, looking aft 25° from perpendicular, looking down 10° from level").

- At least one small metallic target, visible on the x-ray image, should be placed against the surface and its exact location recorded, for example "Target between frames 25 and 26, on seam between planks 2 and 3, port side". The target should be placed so as not to interfere with any fastenings (between frames and on a plank seam, in the case of images of plank fastenings, is probably the best location). The relation of this target to the visible image number should also be recorded, possibly with a sketch. This would eliminate any questions about inversion or reversal of negatives, which numbers alone cannot always do (since numbers such as 1, 3, 6, 8, 9, 11, and others look the same or are ambiguous if inverted or reversed), and would help greatly in cases where the image is taken right through the hull, showing fastenings on both sides.

- A photograph should be taken of the image area showing the image number and target applied to the hull, and the frame and plank numbers marked on the hull. Preferably the photo will show an area somewhat greater than the imaged area to assist in orientation.

Even with the type of preparation and documentation recommended above, there will still be cases in which identifying and evaluating the condition of individual fastenings will be difficult in areas having many fastenings close together. Additional markers will help in such cases, and it might help occasionally to place markers at the locations of the heads of individual fastenings at the plank surface before a shot is taken.

However, it may not be necessary to identify individual fastenings in a realistic inspection. If x-ray imaging could provide an idea of the general overall condition of the fastenings, even without the identifying individual fastenings, it could be a valuable tool. In most cases, all of the

fastenings in a particular area and in a similar situation (i.e. planking into the keel rabbett, plank to frame, etc.) will be in roughly the same condition.

III. OBSERVATIONS RELEVANT TO THE INSPECTION OF STEEL-FASTENED VESSELS

Tearing the subject hull apart immediately after it had been inspected by a number of experienced inspectors and surveyors provided a unique opportunity to evaluate the effectiveness of traditional survey techniques. A surveyor typically evaluates the overall structural condition of the hull of a vessel, (in addition to the obvious visual inspection), by tapping the plank surfaces with a hammer or mallet (I use a hammer with interchangeable rubber faces of various densities), listening to the sound of the tapping and feeling the response of the planking with the fingers of the other hand.

A number of people, civilian surveyors (myself included) and Coast Guard inspectors, used this technique on the hull before and during the NDE trials. As far as I know, none of us expressed great concern over the condition of the hull amidships in the lower three planks, including the area where the garboard planks were butted on a frame.

When the hull was taken apart, it was obvious that the original nails in the garboard and second plank amidships (on both the port and starboard sides of the hull) were completely corroded away in the keel rabbett and in the frames, with only the heads, the part of the shanks in the planking, and the bent-over clinched ends of the plank-to-frame fastenings having any metallic core left at all. Those parts of the nails securing the lower edge of the garboard planks which had been embedded in the keel and the parts of the plank-to-frame clinch-nails which had passed through the frames were corroded away to nothing, leaving empty holes filled with rust. When the boat was taken apart, these planks separated with virtually no force from the keel and the frames. This condition did not develop overnight; it is clear that these fastenings were in similar condition for at least the final years of this boat's active service as a passenger-carrying vessel.

Despite the condition of the fastenings in these planks, the planks were not showing any signs of falling off the boat. These planks were no longer fastened mechanically, but were held onto the boat geometrically for two reasons. First, since the planks were still apparently well-fastened toward the ends of the boat, and since the hull surface is longitudinally convex, the planks stayed against the frames amidships despite the condition of the fastenings. This situation is illustrated in Figure 1. Second, the transverse sections of the hull in this area are concave outside, so the swelling and caulking stresses between the planks push them tightly inward against the frames, the keel, and the floor timbers. This situation is illustrated in Figure 2. Higher up where the hull surface is convex, planks with fastenings in such a deteriorated condition would be pushed off the boat, away from the frames, by the same transverse compressive stresses that keep the lower planks on the boat. Inspecting by the hammer method may be deceiving in areas of concave transverse curvature, since the tightness of the planking to the frames, which is what the surveyor or inspector is feeling for, is not dependent upon the condition of the fastenings, as it is in most other areas of the hull.

While planks which are held geometrically onto the boat may stay in place and their seams may even remain tight under normal use, there is no direct mechanical connection to keep the planks on the boat in the event of a grounding or event involving physical shock which might

spring a plank loose. In a well-fastened hull, heavy weather or a grounding might cause a seam or two to leak, but the fastenings prevent any significant movement of the planking. This hull had no such reserve of strength.

The condition of the butts in the garboard planks was particularly alarming. The garboards were butted on frames, with one straight nail on each side of each butt into the keel rabbett and two clinched nails on each side of each butt into the heel of a frame. Of the twelve butt fastenings (counting both sides of the boat), none had any remaining metallic material in the frame. The only fastening in either of the garboard butts was a recently-installed drywall screw in one side of one of the butts. The x-rays showed that the clinched ends of the original butt nails had been in place when the boat was x-rayed, but when we got the parts back to Groton for detailed inspection, these clinched ends were gone - they had simply fallen off when the boat was cut up because they were no longer connected to anything.

In the case of these butts, the first type of geometric restraint (shown in Fig. 1) does not apply, since there is no fore-and aft structural continuity remaining in the individual planks with the butt fastenings gone. The garboard butts were held in place solely by the reverse curvature of the section (as shown in Fig. 2). This situation was further worsened by the completely deteriorated condition of the nails into the keel rabbett along lower edge of the garboard plank forward and aft of the butt. Despite the condition of these butts, none of us, using traditional survey techniques, had found any cause for great alarm.

The film-type x-rays showed clearly the extremely poor condition of the plank-to-frame clinch nails in the garboard and in the plank above, of the clinch nails in the garboard butts, and of the fastenings from the lower edge of the garboard into the keel.

The results stated above clearly support the policy of visual inspection of fastenings at 5-year intervals laid out in NVIC 7-95. Even though inspection by traditional survey techniques, such as hammering on the hull, did not raise any concerns on this hull, direct visual inspection of the fastenings in this hull, both by x-ray imaging and by actually dismantling the hull, clearly showed the existence of a very dangerous situation. This reinforces the argument which led to the inclusion of a fastening inspection schedule in NVIC 7-95, namely that age alone, without other physical evidence such as obviously loose planking or butts, should be considered sufficient cause for inspectors to require direct visual inspection of the fastenings.

Observations of Corrosion Patterns Relevant to Typical Corrosion in Steel-Fastened Vessels

Several aspects of the patterns of corrosion of the steel nails in this hull, all of which are typical of corrosion patterns of ferrous fastenings in wood hulls, are worth comment.

1. The overall condition of fasteners (due to corrosion) is worse the lower one goes in the hull. Fastenings below the waterline but into frames above the bilgewater level were in much better condition than fastenings which were in parts of the frames that remain saturated constantly or which were in the keel timber.

2. Those parts of the nails which were embedded in the cedar planking were in much better condition than the parts of the same nails which were in oak frames, the oak stem, and the keel (which was birch or maple).

3. The parts of the nails which had the most exposure to oxygen (the heads and the clinched ends) showed considerably less corrosion than those parts of the same nails which were buried in wet wood but isolated from oxygen.

This pattern is typical of the corrosion of steel fastenings in wood. Corrosion requires two reactions. The anode reaction:

$$2Fe \Rightarrow 2Fe^{++} + 4e^{-}$$

results in metal actually wasting away by dissolution (ionization) of the solid into ions which go into solution in the electrolyte (which is water or the water contained in wet wood). In order for the corrosion to continue, the excess free electrons released by the anode reaction must be consumed, or else the accumulation of negative charges in the metal will stifle further corrosion. The cathode reaction:

$$O_2 + 2H_2O + 4e^{-} \Rightarrow 4\,(OH)^{-}$$

consumes the excess free electrons and allows the corrosion process to continue. The cathode reaction occurs primarily where the necessary ingredient (oxygen dissolved in water) is most available, and oxygen generally has the best access to the heads, rather than to the shanks of the fastenings, and in this particular case, to the exposed clinched ends of the fastenings. The parts of the nails on which the cathode reaction is occurring are protected from wastage, while the anode reaction, which actually consumes metal, occurs primarily on those parts to which oxygen does not have ready access, namely the shanks, which are buried in the wood.

At the joint between the planks and frames, the shanks usually have better access to water than other parts of the shanks, but not good access to oxygen. Here, the ions produced by the anode reaction can diffuse away from the corroding nail more easily. This increased diffusion allows the anode reaction to proceed more quickly, so the highest corrosion rate usually occurs near the plank-frame interface.

This selective corrosion of the least-accessible parts of steel fastenings means that <u>the condition of the heads of the fastenings</u>, (even if they are puttied over), <u>and the condition of the clinched ends visible inside the frames is not an accurate indicator of the condition of the buried shank</u>. For the reasons stated above, the shank of a steel nail in wet wood will almost always be in worse condition than the head or the clinched end, and the worst-corroded part of the shank will almost always be at the interface between the plank and the frame or between the plank and other underlying structural members.

4. The corrosion of the steel fastenings did much less damage to the surrounding wood in areas where the wood was saturated with salt water all the time than in areas above the waterline. Along the keel rabbett and in the lowest frame heels amidships, the fastenings were virtually nonexistent, but in these areas the holes where the fastening shanks had been were hardly enlarged at all. At the deck edge, where fastenings from the deck into the sheer strake had corroded due to water trapped under the rub rail, the expansion of these fastenings due to the accumulation of corrosion products had done serious damage to the sheer plank itself.

The explanation for the difference in corrosion product buildup above and below the waterline lies in the ability of saturated areas to hold iron ions produced in the corrosion process in solution and to allow them to diffuse away, and in the lack of oxygen available to combine with these ions to form solid rust in underwater areas. In above-waterline areas there is little opportunity for ions to diffuse away from isolated wet areas, and there is ample oxygen, so iron hydroxide and iron oxide (two solid forms of rust) form readily on the surface of the corroding fastening. Since the rust is much less dense than solid steel, its formation causes the fastening to expand and to physically damage the surrounding wood.

A second cause for deterioration of wood around corroding fastenings is the chemical delignification damage caused by hydroxyl ions, the product of the cathode reaction. Underwater, the cathode reaction usually occurs near the head of the fastening, far from where the wastage is occurring and the iron ions are going into solution. Because the area is wet, the hydroxyl ions can diffuse away from cathode reaction sites without concentrating, while in locally wet areas above the waterline, the area around the local cathodes on corroding metal becomes sufficiently alkaline to damage the surrounding wood. This chemical damage, in conjunction with the physical damage caused by the expanding rust causes problems such as were observed on the starboard side sheer strake amidships of the test vessel.

5. In almost every case the lower parts of the nail shanks, which were were embedded in hardwood, were much more badly corroded than the heads and upper shanks, which were embedded in the cedar planking. This is partially explained by different access to oxygen and the locations of cathodes and anodes. However, three other effects come into play here. First, hardwoods, particularly oak, are more chemically aggressive towards the zinc galvanizing layer and towards steel than is cedar. Second, the saturation moisture content (the maximum possible moisture content after long-term immersion) of northern cedar is extremely low compared to that of oak and other hardwoods, so the lower shanks of the fastenings are actually in wetter material, despite it all being underwater. Third, water (and the ions dissolved in it) travel much more readily through ring-porous hardwoods like oak (primarily along the grain direction) than through cedar. This mobility allows ions produced from the corrosion of fastenings in oak to be carried away more readily than in cedar, which in turn allows more corrosion to occur.

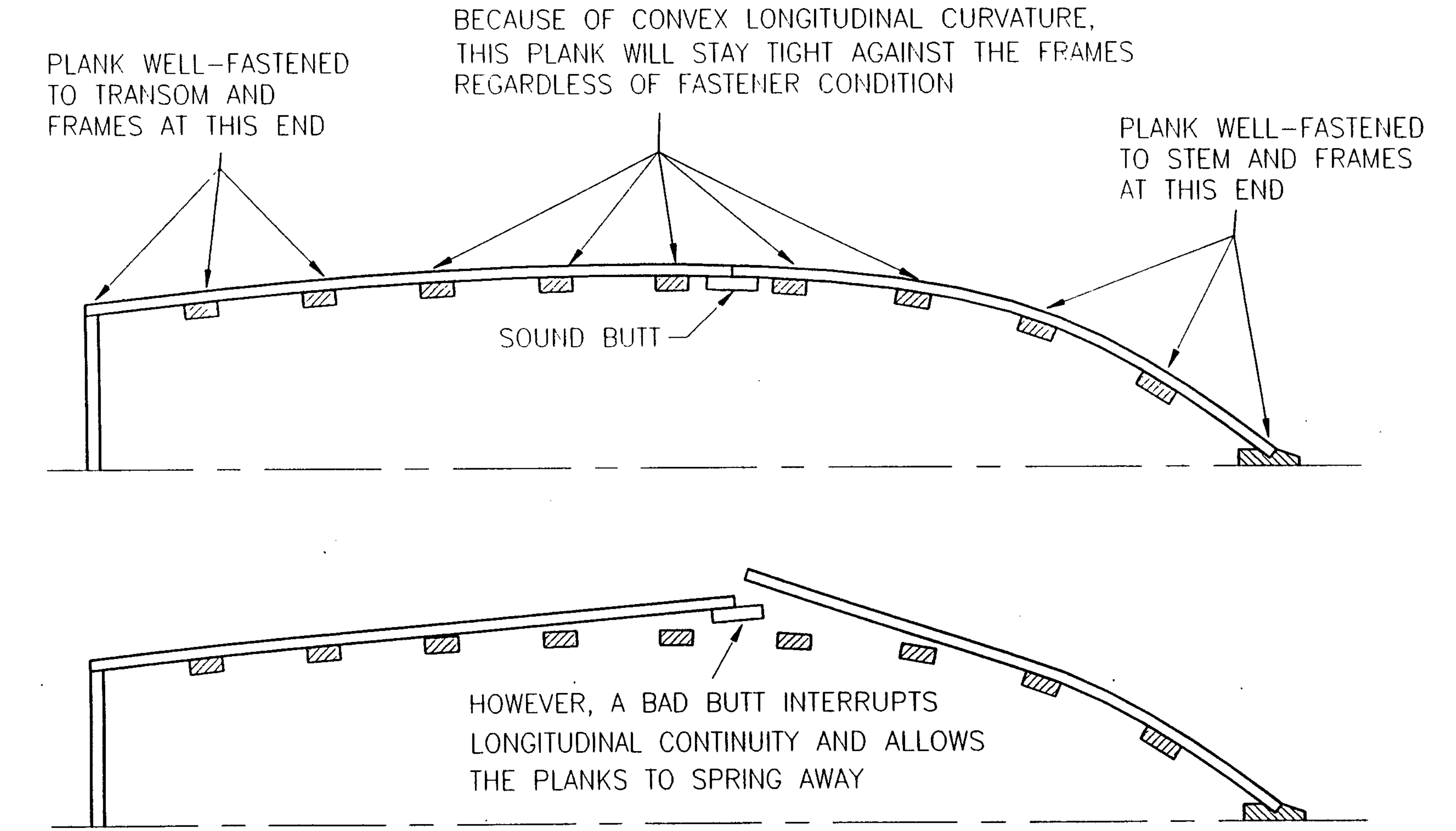
PLANK WELL-FASTENED
TO TRANSOM AND
FRAMES AT THIS END
BECAUSE OF CONVEX LONGITUDINAL CURVATURE,
THIS PLANK WILL STAY TIGHT AGAINST THE FRAMES
REGARDLESS OF FASTENER CONDITION
PLANK WELL-FASTENED
TO STEM AND FRAMES
AT THIS END
SOUND BUTT
HOWEVER, A BAD BUTT INTERRUPTS
LONGITUDINAL CONTINUITY AND ALLOWS
THE PLANKS TO SPRING AWAY
\CG\PLAN.DWG

FIG. 1

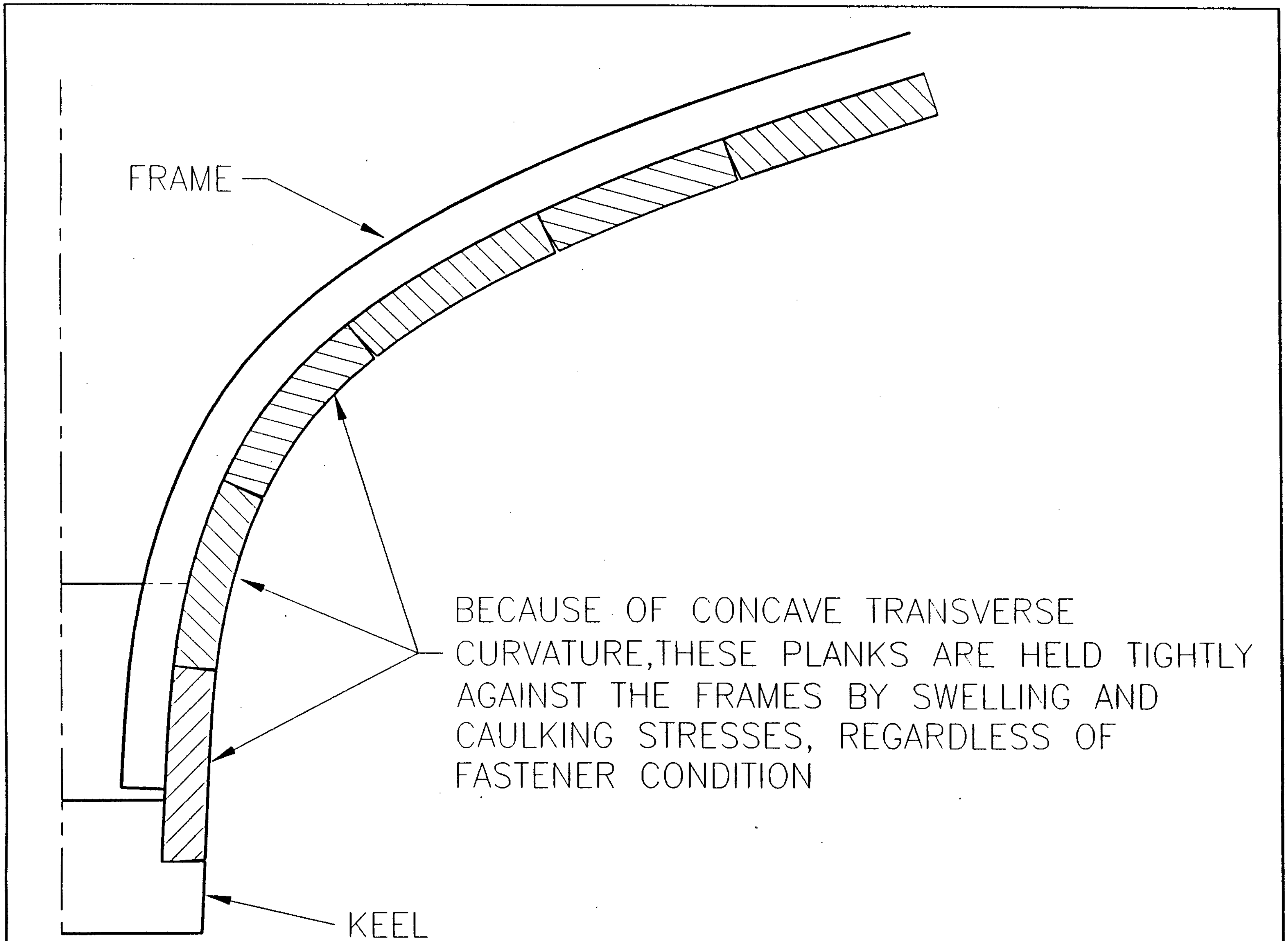
FRAME
BECAUSE OF CONCAVE TRANSVERSE CURVATURE,THESE PLANKS ARE HELD TIGHTLY AGAINST THE FRAMES BY SWELLING AND CAULKING STRESSES, REGARDLESS OF FASTENER CONDITION
KEEL
\CG\SECTION.DWG

FIG. 2

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